

Geologic Site Characterization of the North Korean Nuclear Test Site at Punggye-ri: A Reconnaissance Mapping Redux

A Revised Geologic Map and Report Employing Reconnaissance-based
Geomorphometrics and Geospatial Visualization Techniques

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Abstract:

By the early 2000s, the Democratic People's Republic of Korea (DPRK, or North Korea) established an underground nuclear test site 17 kilometers north of the village of Punggye-ri, at the foot of Mt. Manthap in North Hamgyong Province in the northeastern part of the country. To date, North Korea has conducted three tunnel-emplaced (underground) nuclear explosive tests: on 9 October 2006, 25 May 2009, and, most recently, on 12 February 2013. Recent advances in seismic monitoring (in conjunction with information from openly available commercial satellite imagery) have made possible the very precise determination of the test locations with a resolution of a few hundred meters (See Appendix A).¹ Such precision raises the salience for a more accurate geologic site characterization that could provide:

1. A better understanding of host rock integrity and geologic coupling characteristics,
2. A means to facilitate a more accurate determination of explosive yields.
3. A better understanding of event containment and the likelihood of venting, and
4. An enhanced understanding of the potential radionuclides transport mechanisms that might assist in future monitoring and verification of any future tests.

This study was prompted by the need for more precise mapping and characterization of the geology of North Korean nuclear test site, given that precise, large-scale (1:50,000 or better), ground-survey-sourced geologic maps are entirely lacking for the immediate area of North Korea's underground nuclear test site near Punggye-ri (at least outside of North Korea). Information from several sources was integrated in this study, including previous, publicly available, ground survey geologic mapping studies (some of which date to the 1920s and 1930s), United States Geological Survey (USGS) research and reporting in 2008 and small-scale reconnaissance mapping effort in 2010, coupled with what could be derived by application of LANL-developed geomorphometric analysis methodologies. Original commercial satellite imagery-based imagery analysis and 3-D geospatial visualization tools and techniques were also employed to further refine the geologic site characterization.

The key findings of this study can be summarized as follows:

1. This study demonstrates a low probability for the existence of Precambrian (Proterozoic, “Matenrei”) limestone/dolomite in the immediate vicinity of the nuclear test site, which also mitigates the likelihood of any prompt venting due to non-condensable carbon dioxide gas generation².
2. There is sufficient evidence to infer that some sort of lithological boundary separates different composition basement host rocks at the foot of Mt. Manthap within the main area of the Punggye-ri nuclear test site proper.
3. The 2006 nuclear test occurred (via the “East Portal”) in basement host rock characterized as highly foliated and highly fractured, either Precambrian Saitoku gneiss (as mapped) or “Meisen schistose granite” probably of Mesozoic/Jurassic age (and exhibiting attributes similar to the nearby Saitoku quartz porphyry).³
4. The 2009 and 2013 tests occurred (via the “West Portal”) in a more competent plutonic host rock, either Mesozoic/Cretaceous Tokureido diorite⁴ (as mapped), a very hard rock comparable to granite, or, alternatively, a less fractured variation of a Mesozoic granite, which, in either case, likely provides better containment and better coupling.⁵ Note: New tunneling at the “West Portal” (subsequent to the 2013 test) is ongoing, and additional nuclear testing can be expected to occur in that same competent host rock sometime in the future.
5. Such geologic differences could be one possible contributing factor in the prompt release of detected radionuclides associated with the 2006 event; and explain why the eastern tunnel complex was subsequently abandoned; and provide a reason why the 2009 and 2013 events did not vent (apart from a late detection in 2013, possibly the result of a post-event reentry in April 2013).
6. Additional tunneling at a third portal (at the “South Portal”) is evidently located in host rock that is similar to that used in association with the latter two tests (but perhaps having higher water saturation).
7. A stratified Quaternary volcanic sequence (likely including basalts, tuffs, and rhyolites) is readily distinguishable and forms the top 200 meters of Mt. Manthap and includes a thin capping layer of Shintokuri olivine basalt (evident as a prominent scarp along the western and northern portion of the test site). This sequence lays unconformably upon the basement rocks situated within the test site proper.

Recommendations for future work include a spectral analysis of the most recently excavated spoil material from both the “West Portal” and the “South Portal” and the recently exposed sections of bedrock on the western slopes using HYPERION hyperspectral

data, and to obtain a higher resolution (1 meter) digital elevation model (DEM) to more precisely cross-correlate ground survey-mapped areas with non-ground survey-mapped areas. Evaluation of the topography-geology relationship at the NNSS (Nevada National Security Site) suggests that a DEM resolution of about 1 meter is required to optimize the extraction of terrain characteristics that can be used to characterize the underlying lithologies. The application of commercially available high resolution synthetic aperture radar (SAR) imagery could also help to shed new light on the underlying lithologies and the extent of foliations and fracturing; and, if both pre- and post- test radar imagery for each event (including any future events) could be obtained, interferometric coherent change detection would likely also reveal subtle surface disturbances yielding even greater precision with respect to the event geo-locations.⁶

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Preface:

This report is a deliverable product for the Department of State Announcement (BAA) # 2013-DOS--AVC-VTRDN, Contract #SIAA13AVCVTT0005, under Work Unit RNAN by Los Alamos technical lead David Coblenz and Los Alamos research staff, in support of the U.S. State Department's Office of Verification and Transparency Technologies (AVC/VTT), conducted the study for this report jointly. Report authors David Coblenz and Frank V. Pabian wish to particularly acknowledge and are indebted to the critical assistance of John R. (Rod) Matzko and Peter Chirico of the United States Geological Survey, Reston, Virginia for their gracious support in conducting this follow-on study based upon their own path-breaking research and reporting.

Introduction:

Precise, large-scale (1:50,000 or better), ground-survey-sourced geologic maps are entirely lacking for the immediate area of North Korea's underground nuclear test site near Punggye-ri (at least outside of North Korea), and given that the nuclear test site is a sensitive and denied-access site, such maps are unlikely to become available in the foreseeable future. The available maps for the test site area are of small scale (e.g., varying from 1:500,000 to 1:1 million scale), and include one openly published by North Korea in 1994⁷. High quality large-scale (1:50,000) ground-survey geologic maps do exist for the neighboring regions around the test site, and include a pair of large scale geologic maps (quadrangles) abruptly terminating 12 kilometers south and east of the test site in "folios" of Japanese geologic reporting dating back the 1920s and 1930s. Recent USGS reporting, and associated reconnaissance mapping, drew effectively from those sources. The more recent reporting by the USGS (2010) employed a variety of commercial satellite imagery datasets to create an extrapolative reconnaissance geologic map of the Punggye-ri nuclear test site and environs (see Figure 2). A subsequent Los Alamos National Laboratory review of that effort found that while the conclusions pertaining to an inferred lithological boundary in the eastern half of the test site are plausible, a second inferred lithological boundary (suggesting the presence of dolomite/limestone in an active area of nuclear testing) in the western half of the test site is questionable (see Figure 2 and Figure 3). That review led to a proposal for additional analysis, which formed the basis for this study, with a reevaluation of all available geologic information and commercial-satellite-sourced remote sensing data, and integration of these results with a LANL-derived quantitative

terrain analysis technique in an attempt to derive a clearer understanding of the geologic setting and character of North Korea's Nuclear Test Site at Punggye-ri.

Background

Most Proliferation Detection applications employed to monitor clandestine underground nuclear tests require a high-fidelity 3-D geologic model of the subsurface (e.g., modeling of seismic wave propagation, evaluating potential leakage pathways of radio-nuclides through rock fractures, and *a priori* site characterization and evaluation for treaty monitoring). However, our lack of adequate geologic site characterization for denied-access sites typically limits

representations of the subsurface geology to over-simplified half-space or planar geologic models which compromises our ability to evaluate clandestine tests. There is a clear need for accurate surface geologic maps upon which to build 3-D geologic models.

Figure 1 schematically

illustrates how the surface topography is related to the bedrock geology.

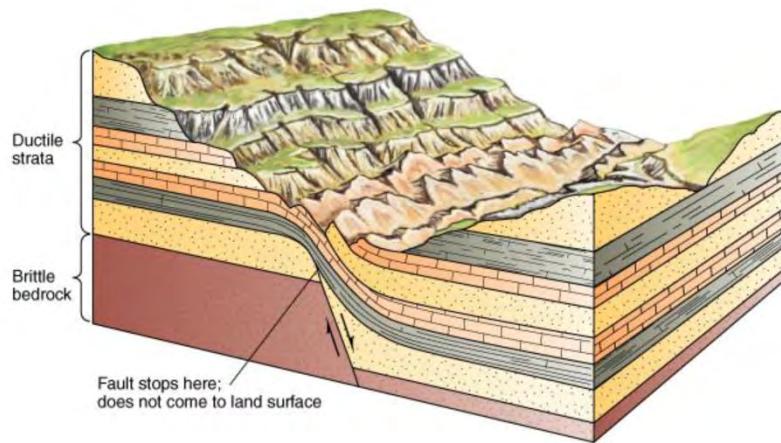


Figure 1: Schematic of the relationship between subsurface geology and surface topography.

One source of information to constrain the surface geology of a denied-access area is the use of commercial satellite imagery for reconnaissance geologic mapping and site characterization. The application of such data specifically for nuclear test sites in denied-access areas for verification applications is not a new one (see review in Prost, 2013⁸). An historical example of the use of remote sensing for geologic characterization was a study conducted by LANL⁹ in 1990 which focused on the Nevada Test Site as a test case and integrated the relevant datasets (including remote sensing data, geophysical data, geological and geomorphological data) to identify and characterize the geology of a region where only incomplete or inaccurate datasets exist (or where direct geological data is

unavailable or unattainable). This study employed the best available imagery at that time which included four primary data sets: Landsat Multispectral Scanner (MSS, 60 meter resolution); Landsat Thematic Mapper (TM, 30 meter resolution); SPOT Multispectral (XS, 20 meter resolution); and SPOT Panchromatic: (Pan, 10 meter resolution). An important conclusion of this study was that despite a limited sensor suite, there was sufficient spatial resolution and spectral band positions to make possible the extrapolation of spectral reflectance and morphologic information into unmapped regions for lithologic discrimination. New procedures for image analysis and thematic map production were beginning to be developed and applied to regions for which there is a paucity of *a priori* geologic information. One method being examined at the time,

*"...extrapolates image product and "ground truth" observations from a previously mapped region into an adjacent region that has been imaged with the same data as the "ground truth" region. The next logical step in the progression of remote sensing applications (and one of our primary research efforts) is the development of "transportable" image processing techniques and feature identification databases that can be used to characterize the geologic environment of an inaccessible region for which there is essentially no *a priori* knowledge ("ground truth") of the region's geology."*¹⁰

The 1990 LANL study concluded that determination of the local subsurface geology requires sound knowledge of the regional geologic setting and that a skilled remote sensing geologist with no prior knowledge about the geology of an area can derive a basic regional geological model by assessing various factors as physiography, geomorphology, structural geology, stratigraphy and lithology, hydrogeology, and vegetation through inferences drawn from both spectral and spatial analysis. Identifications could be derived directly based upon spectral signature (ideally when bedrock is exposed) or through pattern recognition (subjectively by inspection using terrain analysis,¹¹ or, more objectively, using image processing algorithms). As the authors point out:

*"Drainage patterns can provide substantial information on the nature of rock outcrops, e.g., lithology, surface slope, age, and weathering processes that have affected the outcrop. Likewise, the assessment of geographic context and morphology (landform shape and relief) has aided geomorphologists in the identification of landforms and in the interpretation of geologic landscapes."*¹²

This preliminary work has established the fundamental methodology for geologic site characterization of denied-access locations.

Following North Korea's first nuclear test at the Punggye-ri test site in October 2006, geologists at the United States Geological Survey (USGS) applied these principles and undertook a review in 2008 of all available geological information of that area.¹³ They found that a large-scale geologic map was lacking for the area immediately encompassing the Punggye-ri nuclear test site. Although official North Korean Geologic and Tectonic maps were published in 1994 that cover the entire Korean peninsula, both were produced at only 1:1 million scale. The small scale of these maps, along with some notable inconsistencies, limited their utility for detailed geologic site characterization of the nuclear test site. As a result, in 2010, the USGS conducted a remote sensing reconnaissance mapping study to arrive at a clearer and more accurate understanding of the geologic setting of the North Korean underground nuclear test site.¹⁴ That study involved an interpretive extrapolation from a combination of three larger scale (1:50,000) geologic map folios (quadrangles covering areas south, southeast, and east of the test site produced in the 1920s and 1930s by the Japanese¹⁵) together with both low resolution (varying from 15-90 m) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 14-band multispectral satellite imagery and GeoEye high resolution (1.8 m MS and .44 m PAN) commercial satellite imagery. Spectral analysis was also conducted using the ASTER imagery, and surficial geomorphic comparative analysis was based on the global digital elevation model (GDEM) generated from the ASTER imagery through a joint effort with NASA and Japan's Ministry of Economy, Trade and Industry (METI). The USGS study acknowledged the limitations of the resultant extrapolations (particularly given stated limitations associated with the spectral profile analysis) for geologic mapping of the nuclear test site proper, but nonetheless concluded:

"While this interpretation relies heavily on subjective qualitative interpretations of the structural and spectral characteristics of the geology, it remains the best approximation that can be made with the available information."

One of the problematic features of the USGS mapping is the close proximity of an inferred geologic boundary between diorite and dolomite/limestone rock (see

Figure 2 and Figure 3) to the 2009 and 2013 underground nuclear test epicenters, which is at odds with the strong likelihood of containment failure near such an interface².

Furthermore, there has been no established basis for understanding the possible radioactivity venting mechanisms for the 2006 test, as compared to the higher yield 2009 test which did not leak (beyond the argument that larger tests are more likely to create “stress containment cages”¹⁶). Nor had an objective basis been established for determining the likelihood of such venting occurring as a result of any future nuclear testing in the area.

This study is the first to address these issues specific to Punggye-ri Nuclear Test Site geology. We integrate subjective inspections involving commercial satellite image analysis with an objective quantitative “geomorphometric” approach that extracts the terrain characteristics that are indicative of the underlying geology. Additional information used in this study includes more recently available open-source geospatial information about the locations of the test events, quantitative image processing techniques, and the availability of a high resolution (5-meter) digital elevation model (DEM) for the site.

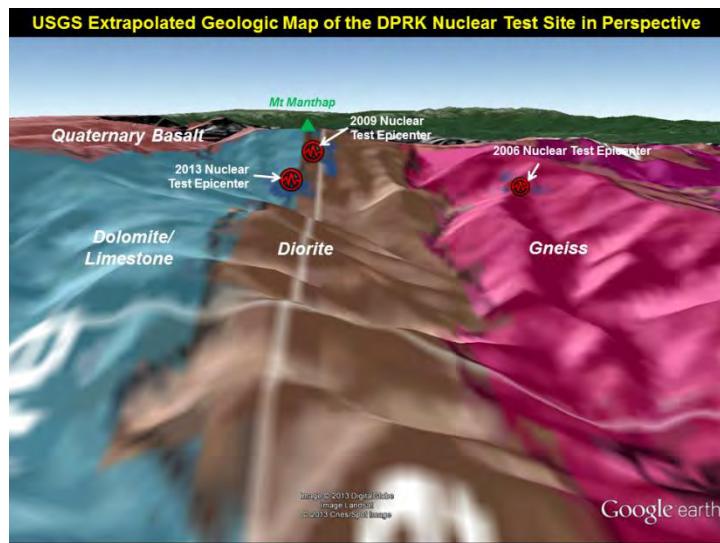
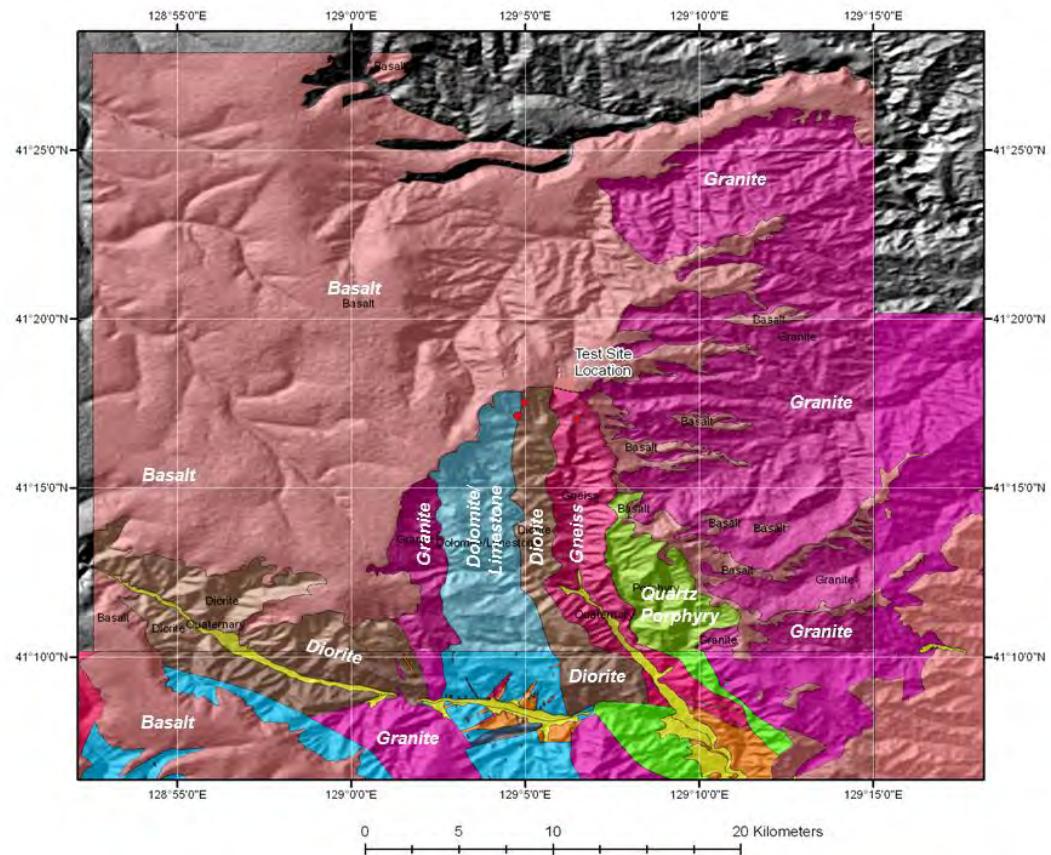


Figure 2: USGS reconnaissance based geologic interpretation (incorporating ASTER spectral data)

Upper: USGS extrapolated geologic map for the Punggye-ri nuclear test site.

Lower: Close-up of the USGS geologic map overlaid on Google Earth. Image has been tilted to view in perspective looking north (epicenters as determined from reference #1).

(After Chirico, 2010, p. 11)

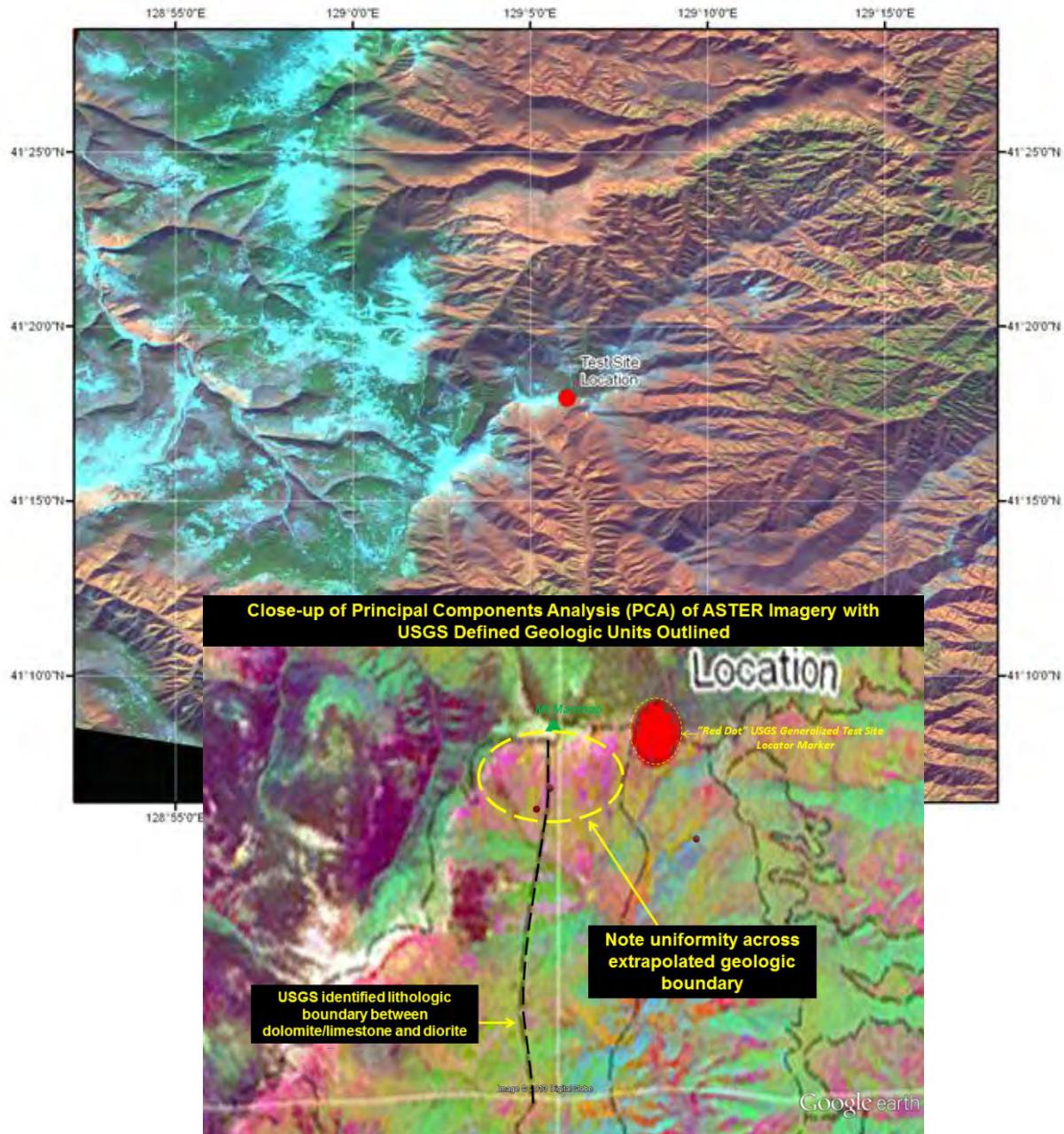


Figure 3: ASTER imagery data for the Punggye-ri nuclear test site.

Upper: Coverage of the ASTER data used to derive the USGS geologic map of the Punggye-ri nuclear test site.

Lower: Details of the USGS PCA map using ASTER imagery illustrating the lithologic boundary between inferred geologic units. Note the two lithologic units have no discernible differentiation in the area closest to the 2009 epicenter (from Chirico, 2010, p.13).

Regional Geological Setting

The following description of the regional geological setting is excerpted from an unpublished *Summary Statements, Geological Atlas of Chosen, Folios 3, 4, and 14* by John R. (Rod) Matzko of the US Geological Survey on 27 Aug 2008.

"The FY08 study of the geology at the location of the North Korean underground nuclear test of October 2006 suggests that the test occurred in Jurassic-aged granite of Mt. Manthap in the northeastern part of the country. A North Korean geologic text states that Manthapsan is a multiphase intrusion into carbonate rocks of the Puktaechon Series, dipping 40 to 70 degrees towards the country rock. The first phase consists of diorite and quartz diorite; the second phase is mainly granite; the third phase is mainly alaskite. Mt. Manthap is part of the very large Kwanmobong batholith of the Hyesan Complex, related to the Songnim tectonic Movement.

Structurally, the area of the test site occurs within the Machollyong Massif, which is sandwiched between the Rangnim Massif on the west and the Kwanmo Massif on the east. The Rangnim and Kwanmo Massifs were originally one structure; they became separated by an ancient rift-type geosyncline into which the thick carbonate rocks of the Matenrei (or Puktaechon) Series accumulated. The Machollyong Massif was subjected to tectonic movement during the late Lower Proterozoic and again during the Mesozoic, folding and fracturing the existing rocks. The Songnim movement also introduced the Mesozoic granitic rocks into the region.

The majority of rocks mapped in the area of the test site are low porosity granitic, basaltic and rhyolitic rocks with associated tuffs, and metamorphic rocks, with lesser amounts of sedimentary rocks. The metamorphic rocks are mostly schists, fewer types of gneiss, and some metamorphosed sedimentary rocks such as marble and quartzite.

A widespread, thick carbonate sequence (the Matenrei or Puktaechon Series, of Lower Proterozoic age) is mapped to the south of the test site (Folio 14); a small-scale map shows these rocks surrounding Mt. Manthap.

The carbonates are of interest because of the potential containment problems they present, and their presence may limit the locations of future tests in this region. The large-scale maps also indicate that blocks of carbonates are preserved within the granite masses as roof pendants.

The large-scale geologic maps (available only for the areas south and east of the test site) also show wide distribution of geologically young (Quaternary and Tertiary) acidic (rhyolitic) and mafic (basaltic) volcanic rocks in areas south of the test site; the youngest have been dated to the Pleistocene. The relatively low resolution maps (small scale) 1:1 million scale maps (which do cover the area of the test site) likewise show extensive development of Quaternary mafic volcanic rocks to the north and west of the test site along an Achaean plutonic boundary (granite) within the test site proper."

Figure 4 shows the extent of the Japanese geologic mapping from the 3 key Japanese "Folios" (Nos. 3, 4, 14) located closest to the Punggye-ri nuclear test site as overlain by Buttleman and Matzko onto the smaller scale North Korean geologic map from 1994. The key point is that the compilation corroborates the existence of both Precambrian (Proterozoic) carbonates (dolomite/limestone) and Tokureido diorite (labeled Cretaceous age) being present just south of the test site. The small scale 1994 North Korean map does not show either of those rock types continuing north into the test site proper. However, the "Tanchon Complex Jurassic granite" on the newer small scale North Korean maps appears to be one and the same as the unknown age, but likely Jurassic, "Meisen schistose granite" shown on the older large-scale Japanese maps. A joint North Korean/Chinese report from 2009¹⁷ includes a very small scale map, which similarly identifies the area of the nuclear test site as being situated in the "Middle Jurassic Tanchon Complex," apparently granite, next to "Neogene volcanic rocks," again consistent both with the Japanese mapped Shintokuri basalt and volcanics and 1994 North Korean mapping.

It should be noted that, on the 1994 country level geological map, the North Koreans also show a northwest-southeast trending fault that terminates just west of Mt. Manthap and likely through the area now accessed by the "South Portal". We can neither confirm a fault at this location nor provide insights on any potential impact such a fault might have with regard to future testing in association with the "South Portal." However, the nearly straight, north-south trending valley between Punggye-ri and Mt. Manthap is at least suggestive of

possible local faulting. Nonetheless, in general, the Punggye-ri/Mt. Manthap region is in an area of low natural seismicity.¹⁸

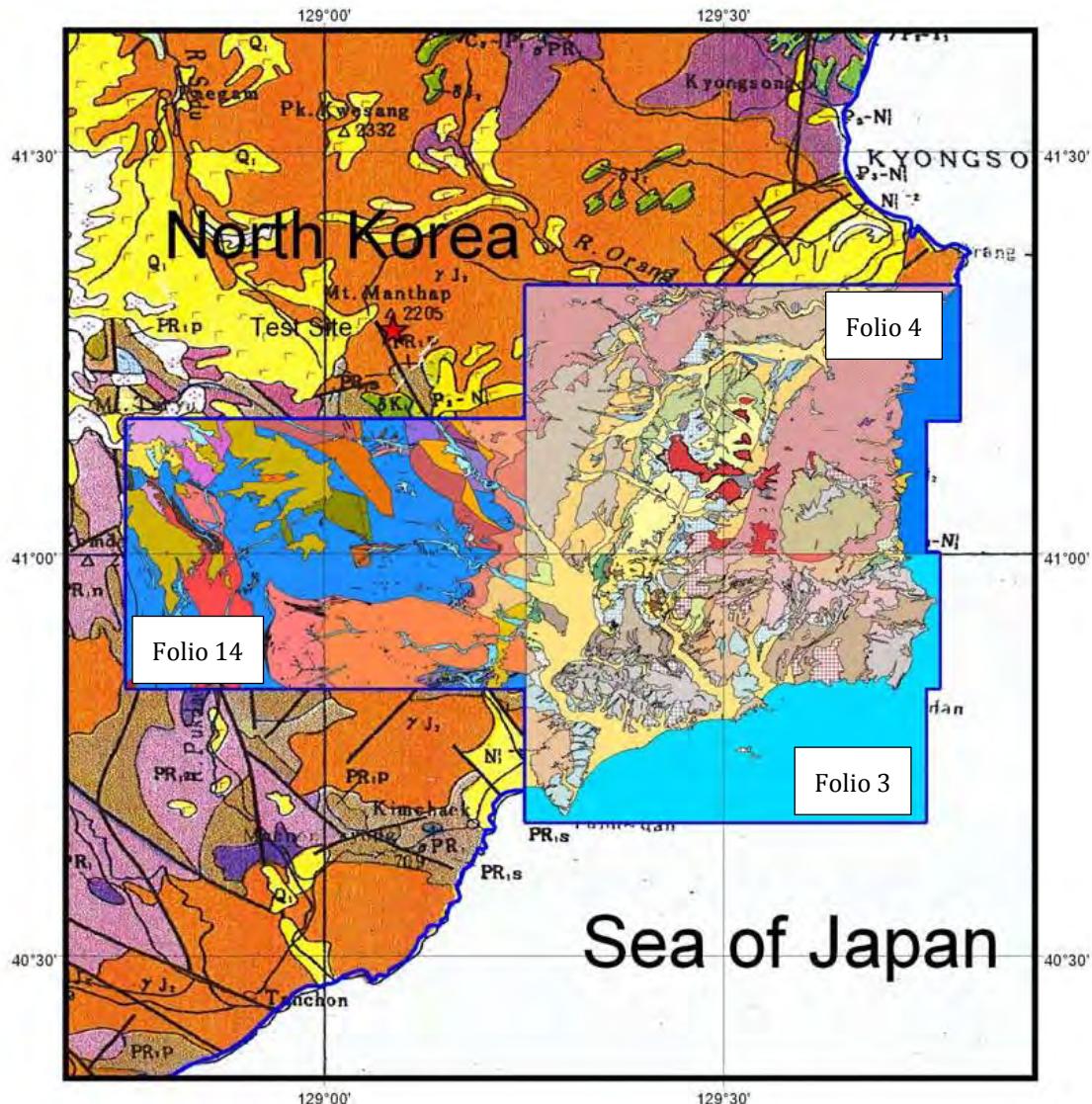


Figure 4: Details of the geological folios 3, 4, and 14.

From of the Geological Atlas of Chosen superimposed on the 1:1M scale geologic map of Korea (Central Geological Survey of Mineral Resources, 1994). The Punggye-ri nuclear test site is indicated by the red star near Mt. Manthap with a NW-SE trending fault just beneath it. (After Buttleman and Matzko, USGS, 2008, p.9)

Summary of Reconnaissance Mapping Methodologies

Various reconnaissance mapping methodologies were employed in the creation of the 2010 USGS geology map of the Punggye-ri nuclear test site by Peter Chirico, who noted:

“...interpretations were made to correlate the previously mapped geologic units to areas where no geology data was available. To extend the geologic map data into the unmapped area, the spectral analysis, Principal Components Analysis (PCA), and DEM data were interpreted with the previously mapped folio mapped information.”

Building upon this effort, we have employed additional reconnaissance mapping methodologies that include correlation with new geomorphometric information as derived from a 5-meter Digital Elevation Model (DEM) of the area supplemented with high resolution Digital Globe commercial satellite imagery (as visualized in 3-D perspective using Google Earth), and integrated with recently published detailed geo-positional information on the Punggye-ri nuclear test site. This approach provides a more objective basis for identifying lithologic units and their boundaries such as are present on the USGS reconnaissance geology map between the mapped Mesozoic diorite (generally more competent rock as manifested by a dendritic (branching) drainage pattern) and mapped Precambrian gneiss (which could be subject to a greater degree of fracture, hence less competent, and generally manifested by a more angular drainage pattern). (See Figure 5 and Figure 6).

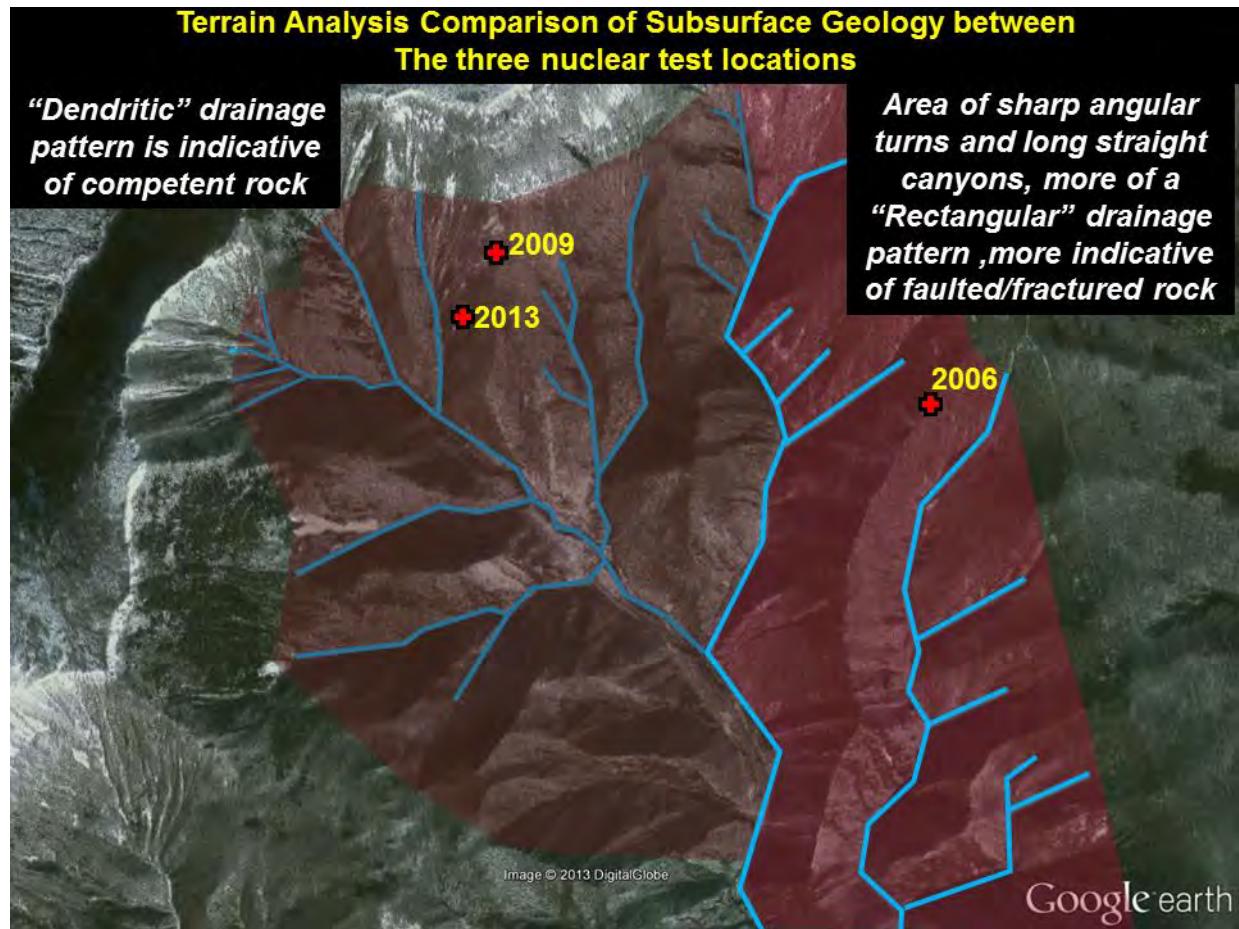
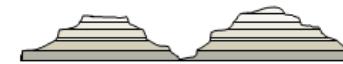
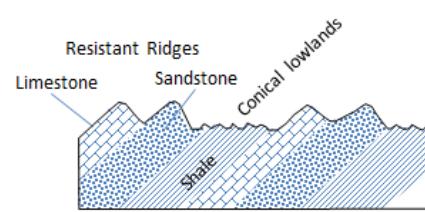
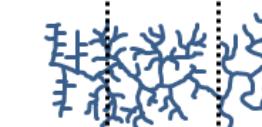


Figure 5: Subjective manual terrain analysis with respect to the openly identified event locations for the three North Korean underground nuclear tests conducted to date.

The drainage pattern suggests a differential stream pattern consistent with two different rock types along a lithologic boundary as inferred and mapped by the USGS and separating the two types of host rock associated with underground nuclear testing.

Rock Type <u>Sedimentary</u>	Structure	Drainage Pattern
Flat-Lying Sedimentary	 <p>Contrast between resistant and erodible layers produces steep escarpments. Shale is characterized by more gradual slopes.</p>	 <p><i>Dendritic, Fine Texture</i> Presence of shale increases dissection</p>
Dipping Sedimentary	 <p>Resistant Ridges Limestone Sandstone Shale Conical lowlands</p> <p>Sharp ridge crests associated with resistant layers. The V's formed between the teeth point down the dip of the rock strata. Shale form conical lowland hills.</p>	 <p><i>Dendritic, Fine to Medium Texture</i> Trellis pattern may show parallelism if there is a regional slope.</p>
<u>Igneous/Metamorphic</u>		
Arid Granite	 <p>Bold, massive dome-like hills</p>	 <p><i>Dendritic, Fine Texture</i> Sickle-shaped bends in drainage.</p>
Schist	 <p>Rugged topography with hills and valleys controlled by foliation.</p>	 <p><i>Rectangular Dendritic, Fine Texture.</i></p>
Gneiss	 <p>Steep slopes due to differential weathering.</p>	 <p><i>Angular Dendritic, Fine to Medium Texture.</i></p>

After Way, 1973

Figure 6: Schematic of the relationship between geology, terrain character and drainage patterns.

In general, geomorphic landscape features reflect the interplay between tectonic-associated processes of uplift and climate-associated processes of erosion. The underlying geology controls the character of the landscape for both of these processes. Recent advances in the field of geomorphometrics (defined as the science of quantitative land surface analysis¹⁹) provides a methodology to quantitatively measure landscape features and provide an objective approach for evaluating the geology (e.g., rock type, fault and fracture distributions) that influence the character of landscapes.

Our approach to quantitative terrain analysis is based on three methodologies:

1. An eigenvalue analysis which provides information about the topographic organization and shape factor (a measure of the strength of the dominant linear fabric to the terrain).
2. A measure of the surface roughness based on the “rugosity” of the surface - calculated by computing the average elevation change between a grid cell and the eight neighboring grid cells.²⁰
3. Correlation of the surface drainage network with the bedrock geology and structure.

This information is then integrated with data collected by various remote sensing platforms and mapped and visualized with Global Mapper and Google Earth (together with correlation of available regional geologic maps of the area to refine the geologic site characterization).

Figure 7 provides a high resolution (5-meter) digital elevation model (DEM) map of the Punggye-ri nuclear test site that was generated as part of this study to examine the various stream drainage patterns as an expression and potential indicator of the underlying geology. Most readily identifiable are the feather-like patterns arising in the nearly flat-lying basalt layers. The Oligocene age Ryudo (Yongdong) alkalic basalt in the lower right (southeast) corner of the map is clearly distinguishable from the Quaternary Shintokuri olivine basalt that encompasses the test site on the top and left (western and northern sides).

Figure 8 shows the rugosity (or surface roughness) of the test site as determined from the elevation data. The Shintokuri basalt cap stands out sharply in dark blue on the west and north, while the mapped probable dolomite/limestone roof pendant appears as a light blue ovoid near the bottom center.

Using a correlation algorithm to relate surface roughness to terrain types³⁰, the base terrain types of the NK Test Site provide insight into the geologic setting. Figure 9 illustrates the distribution of the three lowest terrain type orders (measure of surface roughness). The lowest order terrain maps the distribution of basalt caps (primarily the Shintokuri olivine basalts) and the alluvial drainages. The higher order terrain (Figure 9, lower) highlights the distribution of fractured crystalline rock (granites and diorites) and shows how the Punggye-ri nuclear test site is located at the northern extent of these rougher and deformed rocks. The complete terrain map (Figure 10) illustrates how the region of high terrain complexity (rough topography generated by fractured and foliated schists and gneisses) extends up to the area of the NK Test Site. Capping basalts and volcanic layers mask the northern most extent of the basement rock terrain type, but it is reasonable to assume that it continues northward under the basalt and volcanic layers.

Fine-tuning of the terrain type map and conversion to a plausible geologic map requires the incorporation of additional information. For example,

Figure 11 illustrates the synthesis of the topographic data and the surface roughness information to further delineate the location and extent of a limestone pendant. At present, this “data fusion” step is achieved by visual inspection by a trained spatial analyst. It remains as much art as science at this point. Future work would include additional automation of this step.

Our final geologic synthesis map of the Punggye-ri underground nuclear test site is shown in Figure 12 (overview) and Figure 13 (close up). These maps combine all of the available information and are the product of both computer-automated analysis routines and fine tuning by geologic analysts.

Our geologic interpretation confirms that the test site is bordered on the west by the eastern limit of the Quaternary “Paektusan Volcanic Plateau” (Also known as the Kaima Plateau²¹) consisting of a sequence of horizontal volcanic strata including the Shintokuri olivine basalt sourced to the Paektusan (a.k.a. Baitoushan, Hakutosan, Mt. Changbai) volcano, located approximately 110 kilometers northwest of Punggye-ri on the North Korea/China border having geographic coordinates of 42°06' N and 128°04' E. That stratified volcanic sequence (and likely tuffaceous ash falls) forms the top 200 meters of

Mt. Manthap and includes a thin capping layer of basalt that forms a prominent scarp along the western and northern portion of the test site. Dating from about 1.4 million years ago²², the sequence lays unconformably upon the basement rocks situated within the test site proper.

Rockslides, consisting of greyish basalt talus and scree, extend downslope at multiple locations from a break in slope that marks the unconformity boundary. Erosion channels are most prominent beneath gaps in the otherwise generally protective basalt cap and escarpment. Severe flooding in the late summer of 2012 caused marked erosion scars which contributed to downslope scouring of the major steam beds along with adjacent vegetation that exposed bare bedrock in many places within the test site proper (thereby providing new candidate sites for future hyper-spectral analysis).²³

The main area of the test site tunneling underlying these volcanics is situated in the basement rocks, most often described in available reporting as either Jurassic-aged granite, (e.g., “Meisen schistose granite,” see reference 3), but more likely consisting of a variety of rocks in including granite, diorite, gneiss, and possibly quartz porphyry. These basement rocks form a large south sloping and eroded drainage basin.

The eastern portion of the test site, which has been associated with North Korea’s first nuclear event in 2006, exhibits numerous highly foliated and likely highly fractured, outcroppings. Although we have tentatively mapped this lithologic body as an extension of the Saitoku gneiss consistent with Chirico, we also cannot yet rule out it being a western extent of the “Meisen schistose granite,” which would also be consistent with the small scale 1994 North Korean origin geologic map. It should be noted that, according to the Japanese geologist, Yoshio Kinosaki, the rocks of the Precambrian Matenrei System (that include the Saitoku gneiss and the dolomite/limestone) are not only “intensely comingled with each other, but also intruded by so many dikes and lit-par-lit injections of various rocks such as aplite, pegmatite, schistose granite, and schistose diorite, that they cannot be differentiated on the maps.”²⁴ In any case, the host rock for the 2006 underground nuclear test is highly foliated, and likely highly fractured, which might help to explain the prompt venting of radioactivity detected outside of North Korea following that event.²⁵

The western portion of the test site proper, which can be associated with both the 2009 and 2013 underground nuclear tests, has been tentatively identified and mapped as Tokureido diorite, although we cannot yet rule out a less foliated and fractured version of the Meisen schistose granite (or perhaps slightly younger Mesozoic granite like the

Sentoku). In either case, based on our geomorphometrics-based analysis, the host rock directly under Mount Manthap is very likely a hard and competent one, more like diorite or more typical granite, and thus likely a good choice for containing underground nuclear explosives tests.

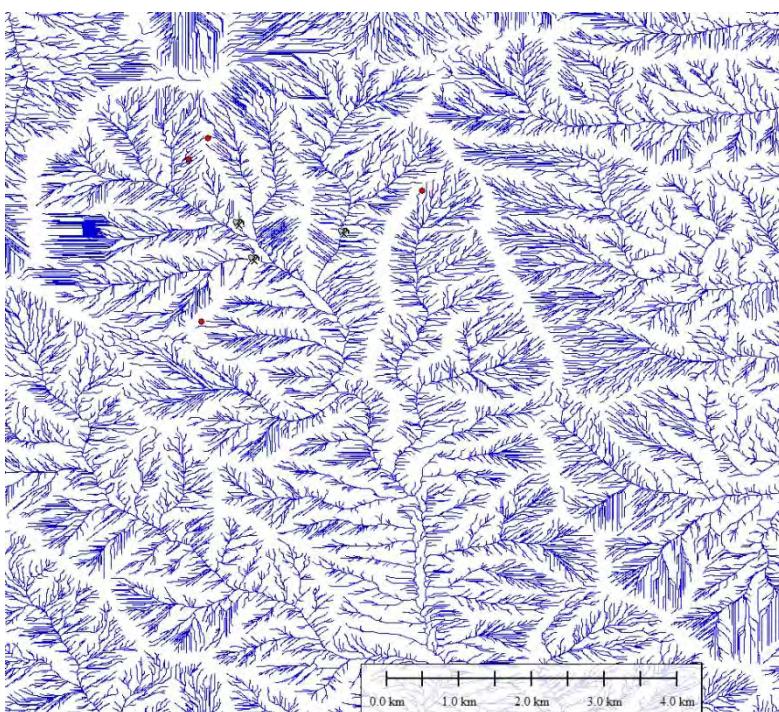
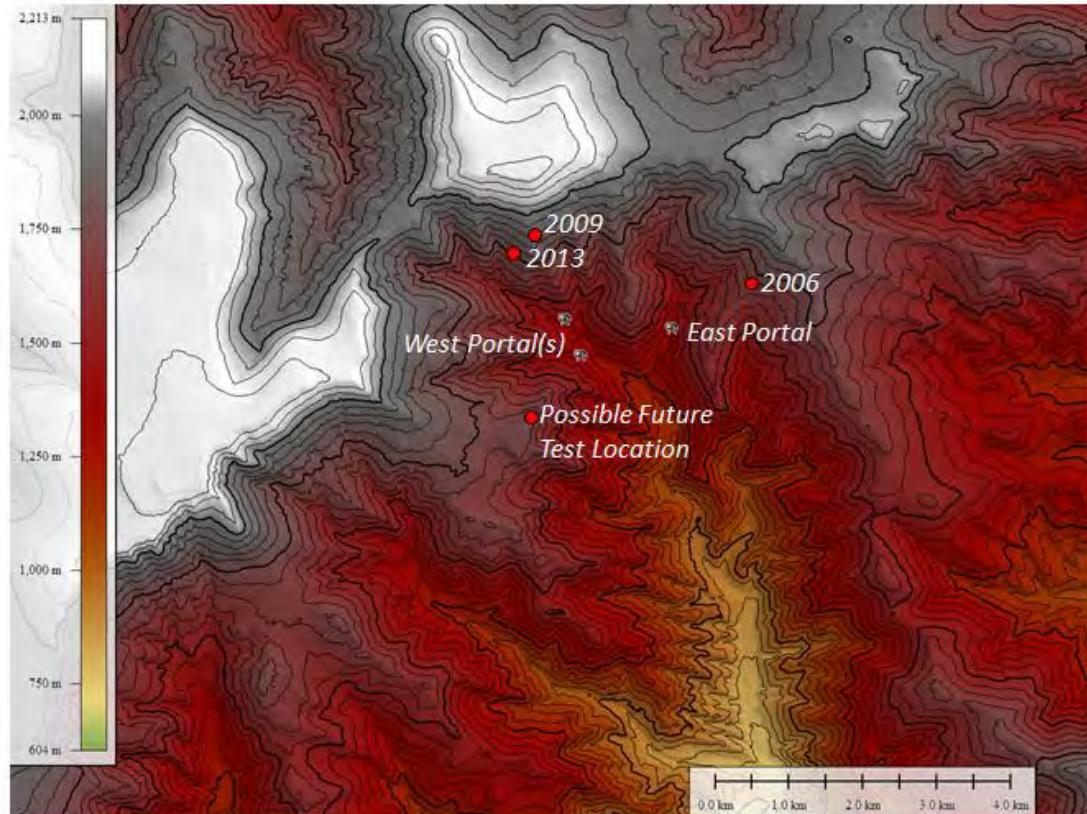


Figure 7: 5 meter DEM and drainage pattern for the Punggye-ri nuclear test site.

Upper: A high resolution (5-meter) digital elevation model map of the Punggye-ri nuclear test site showing the test locations and relative locations of the tunnel portals. Lower: Stream drainage patterns derived from the topographic surface. Variations in

the drainage patterns can be related to the underlying geology.

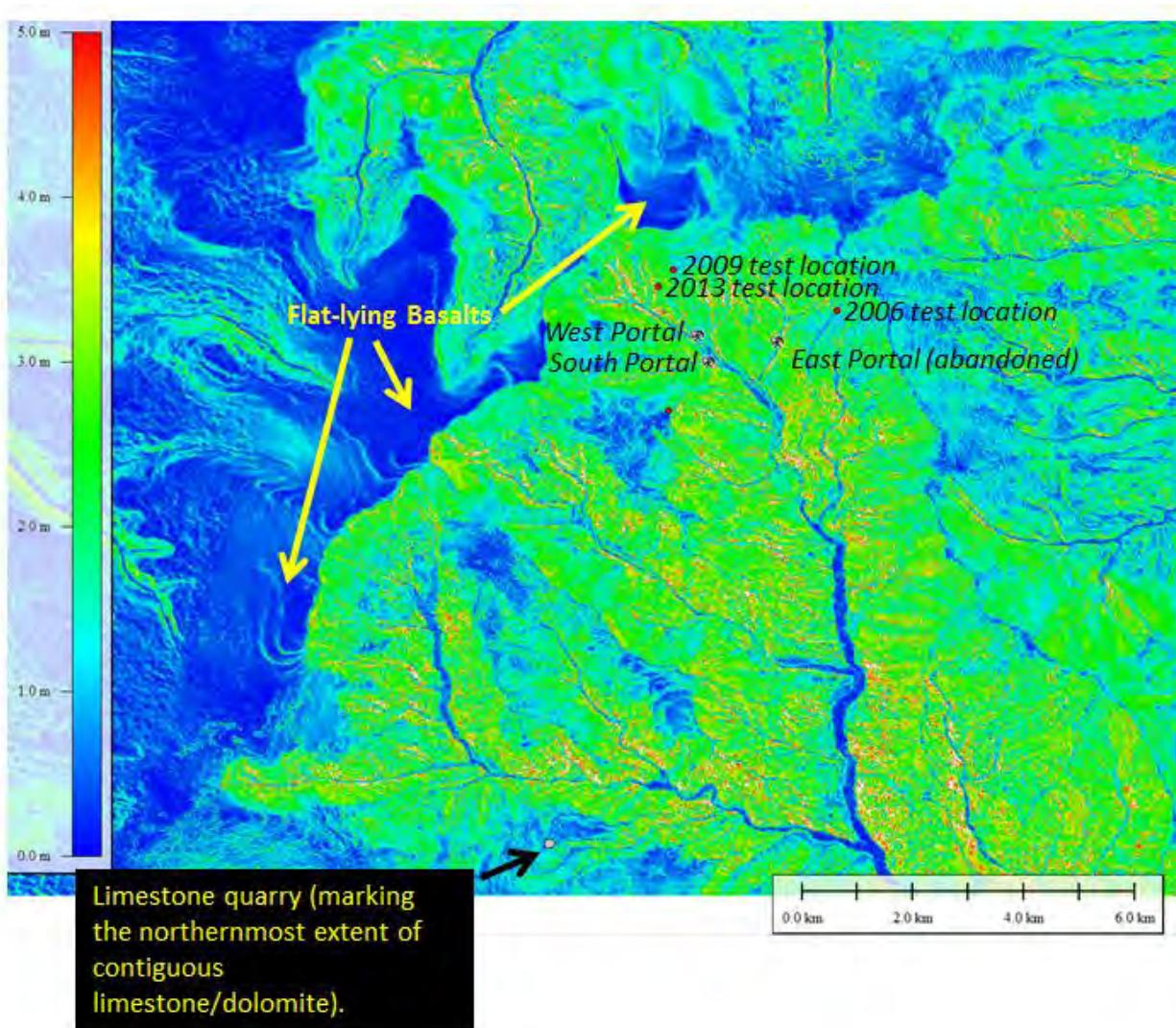


Figure 8: Rugosity (topographic roughness) of the Punggye-ri nuclear test site.

Rugosity is calculated from the elevation data and algorithmically derived near neighbor grid comparisons²⁰.

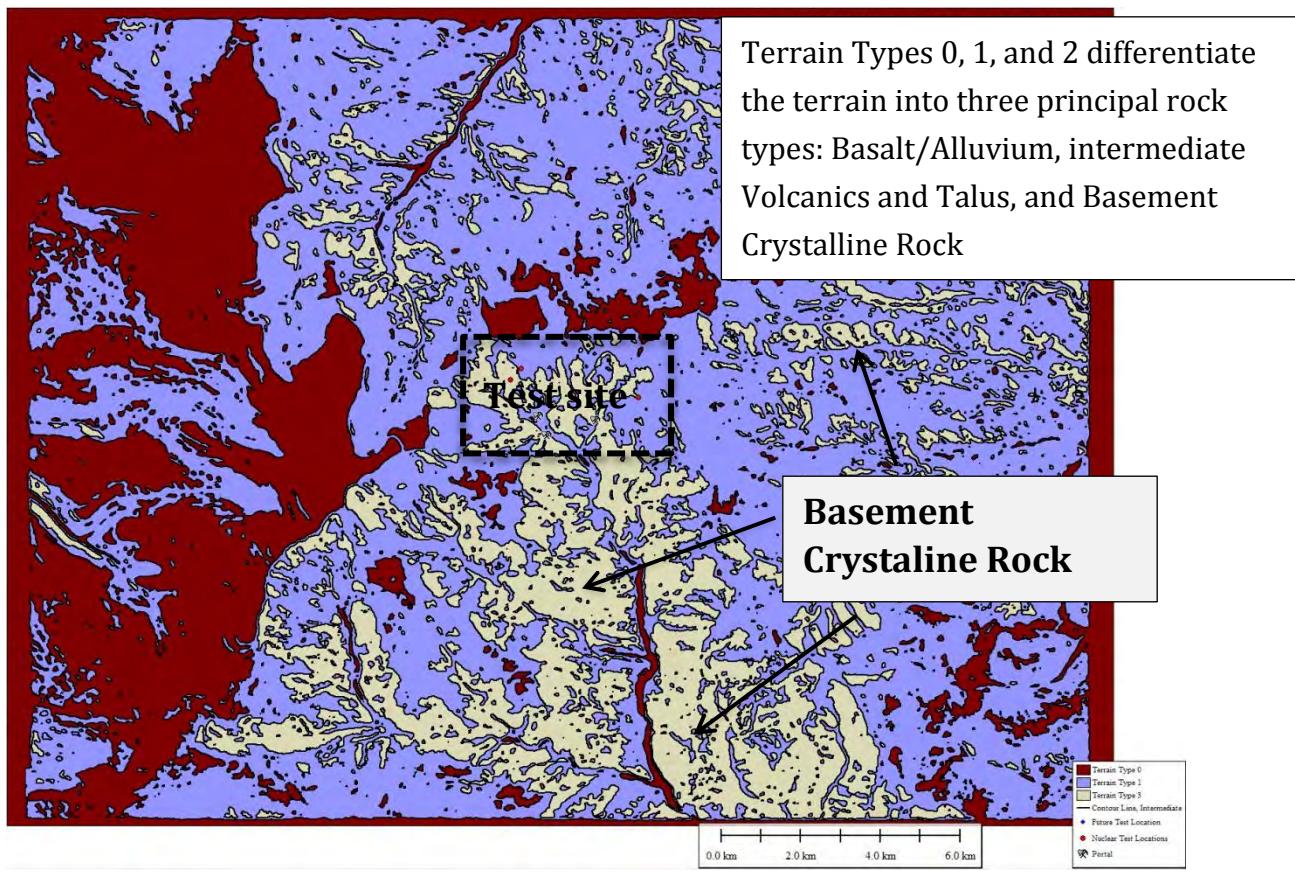
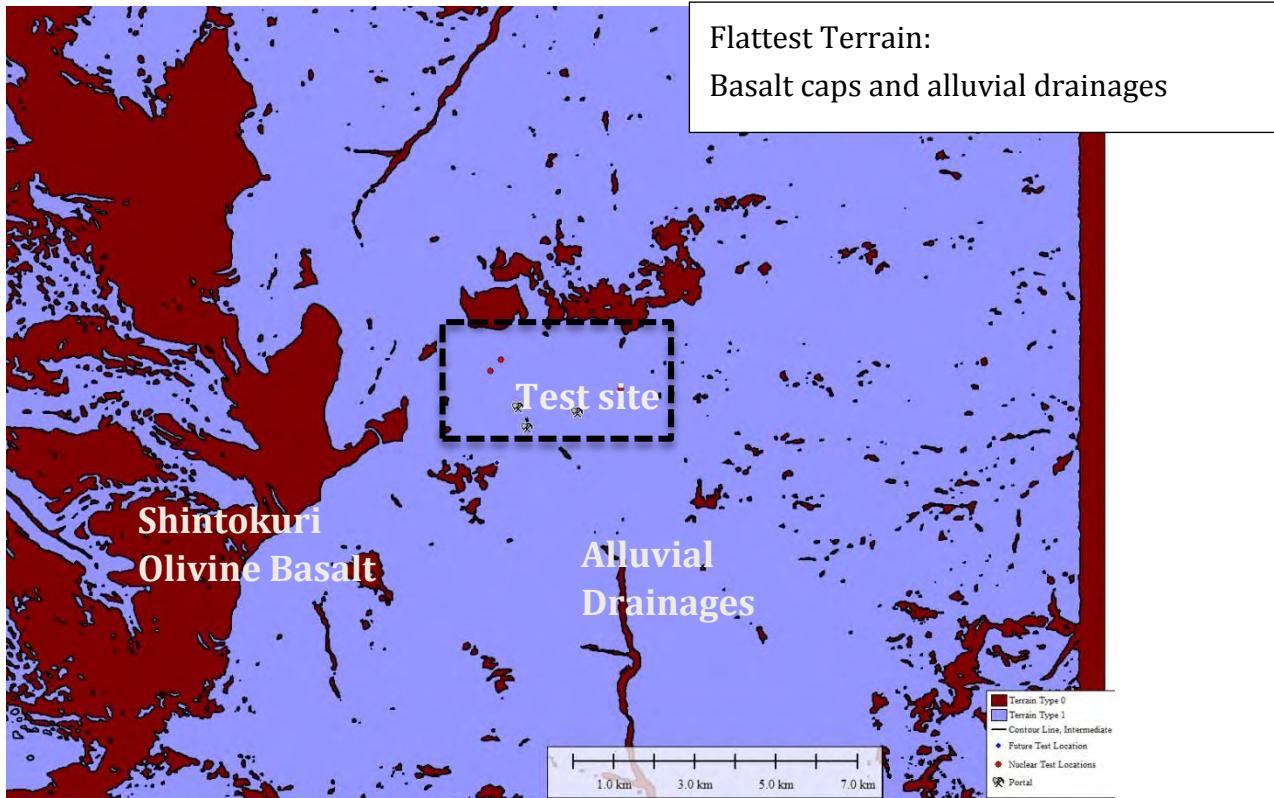


Figure 9: Map of three lowest order terrain types.

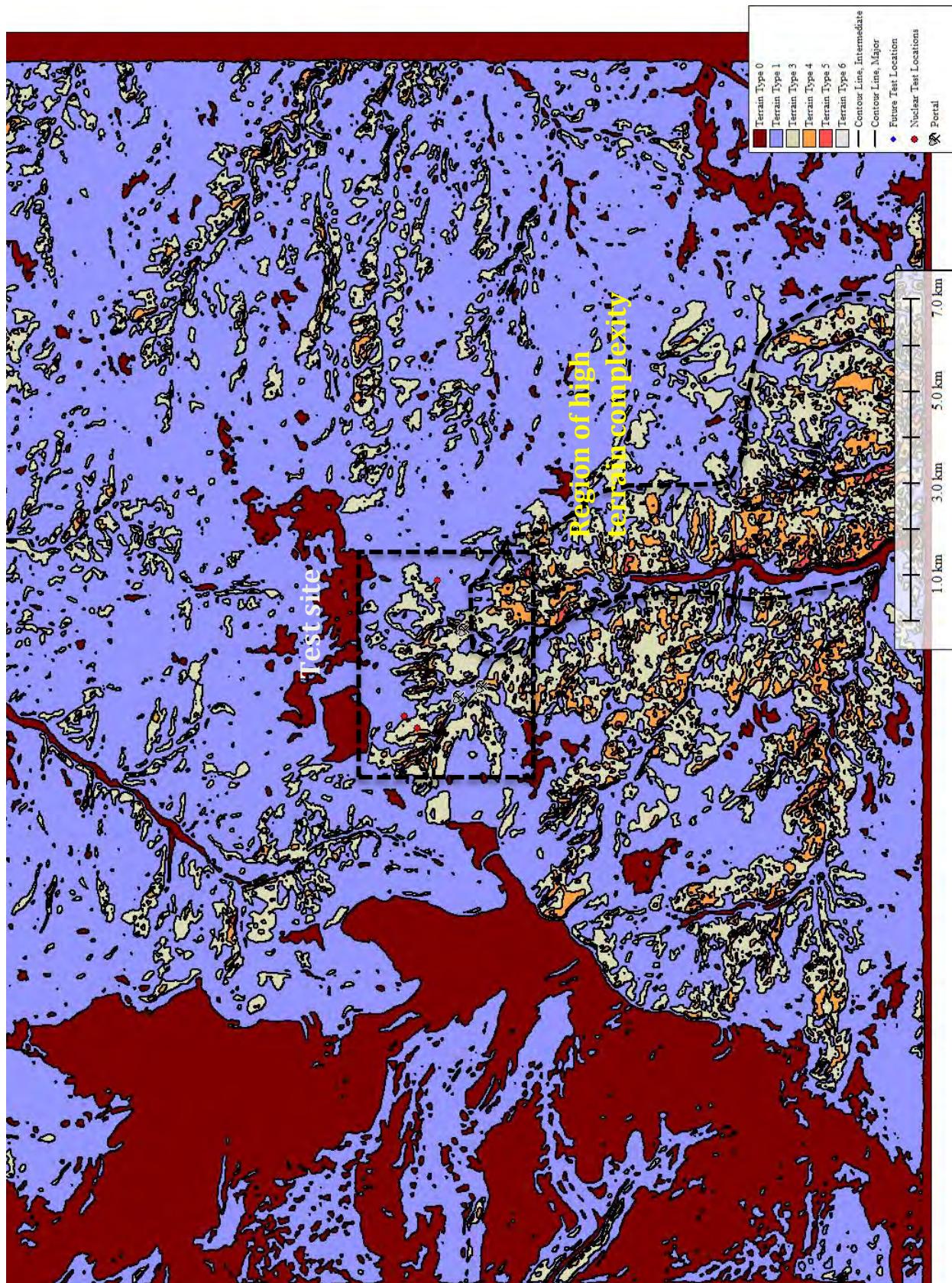


Figure 10: Complete terrain mapping for the Punggye-ri nuclear test site.

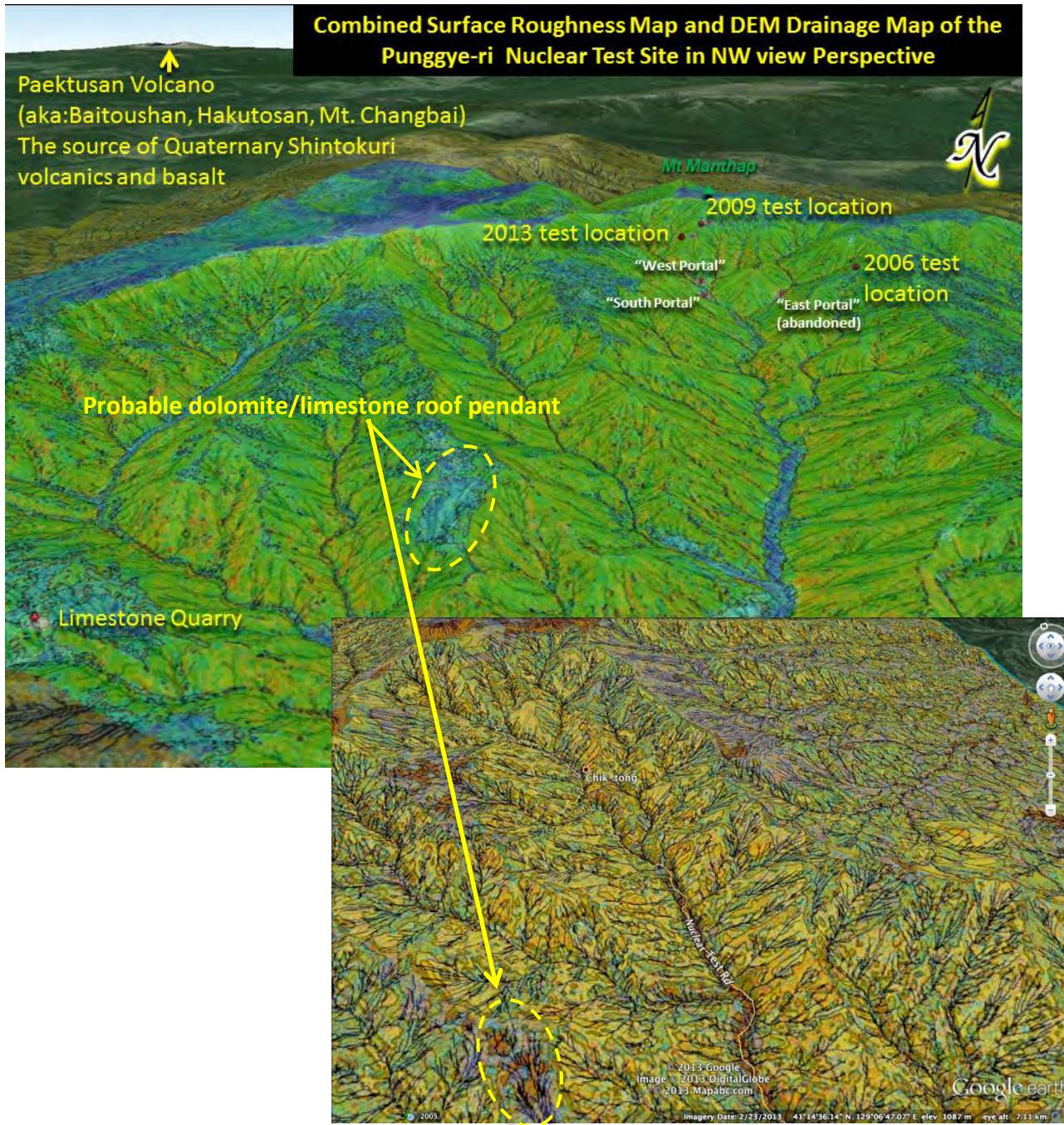


Figure 11: A combined rugosity (surface roughness) map and drainage map for the Punggye-ri nuclear test site.

Upper: The derived stream drainage map is shown in perspective on Google Earth. The probable dolomite/limestone “roof pendant” stands out in the lower left center of this combined image. **Lower:** Terrain types overlain on drainage map, again showing the unique cohesive qualities suggestive of a dolomite/limestone “roof pendant” inside the yellow oval.

**Reconnaissance Geologic Map
Nuclear Test Site
Punggye-ri, North Korea**

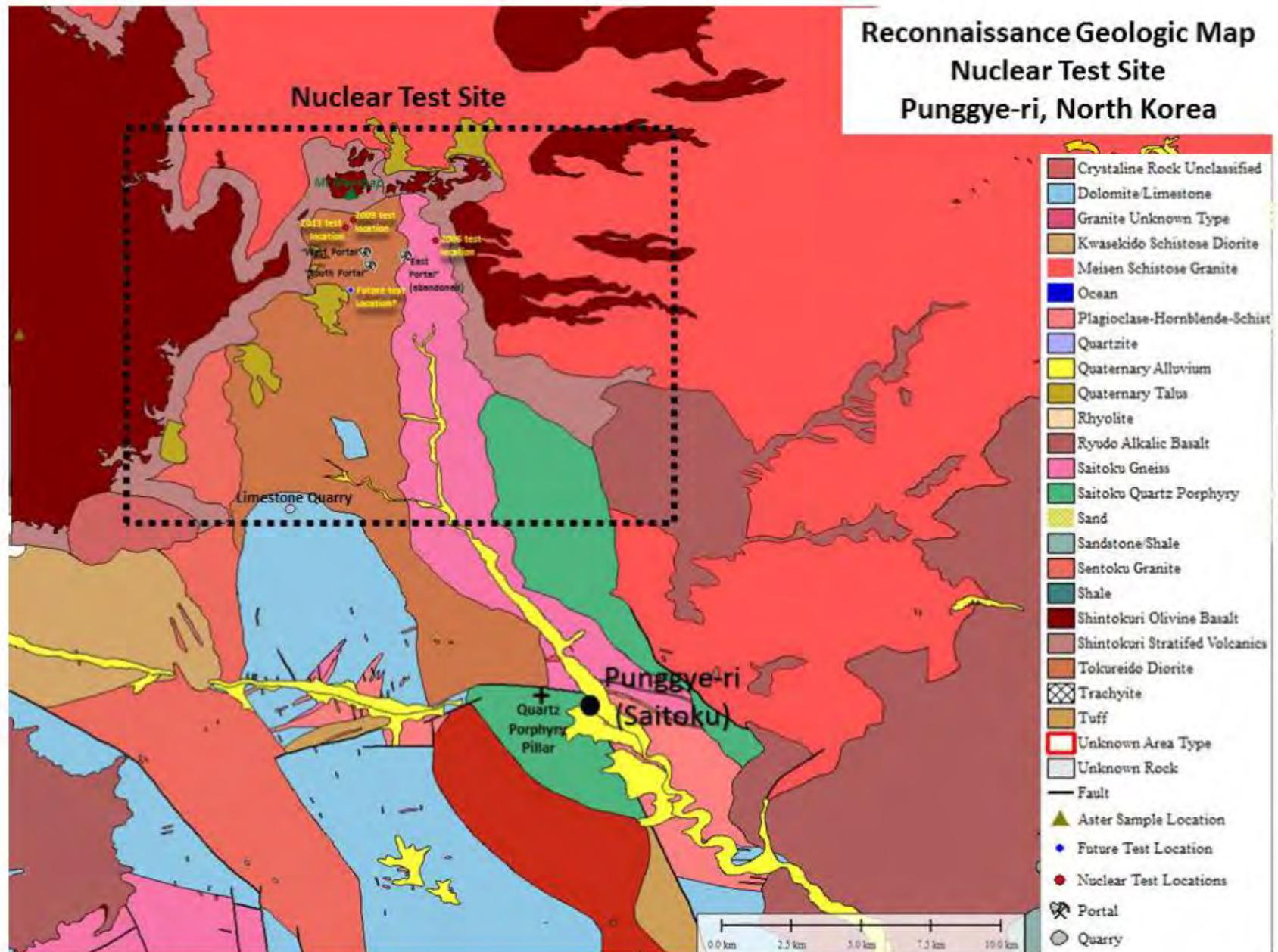


Figure 12: The derived regional geologic map of the Punggye-ri nuclear test site.

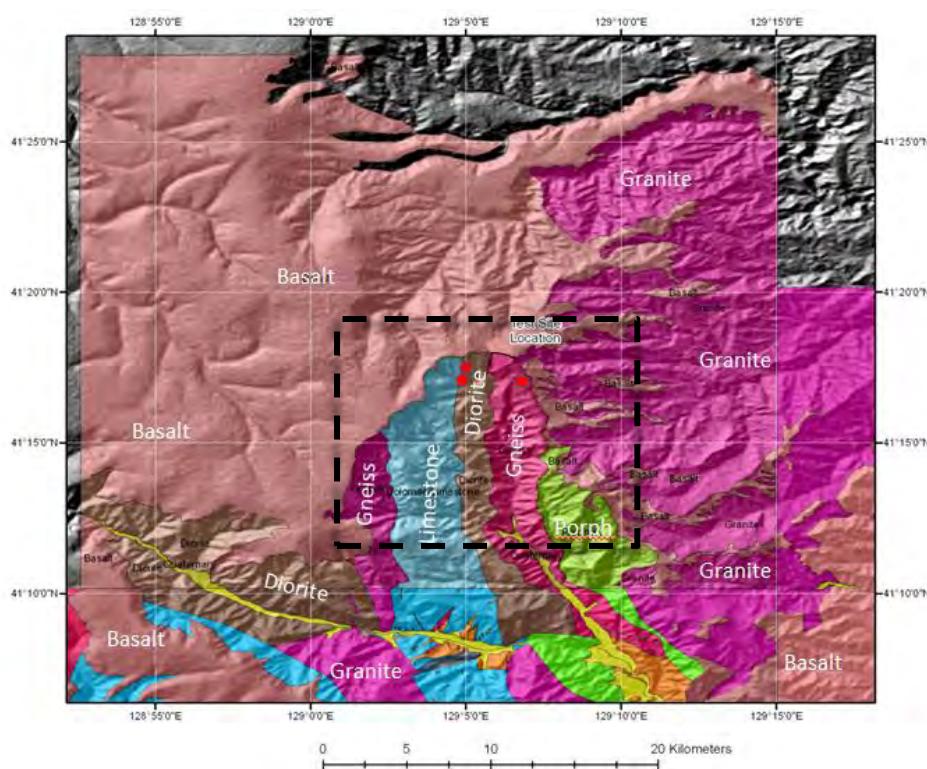
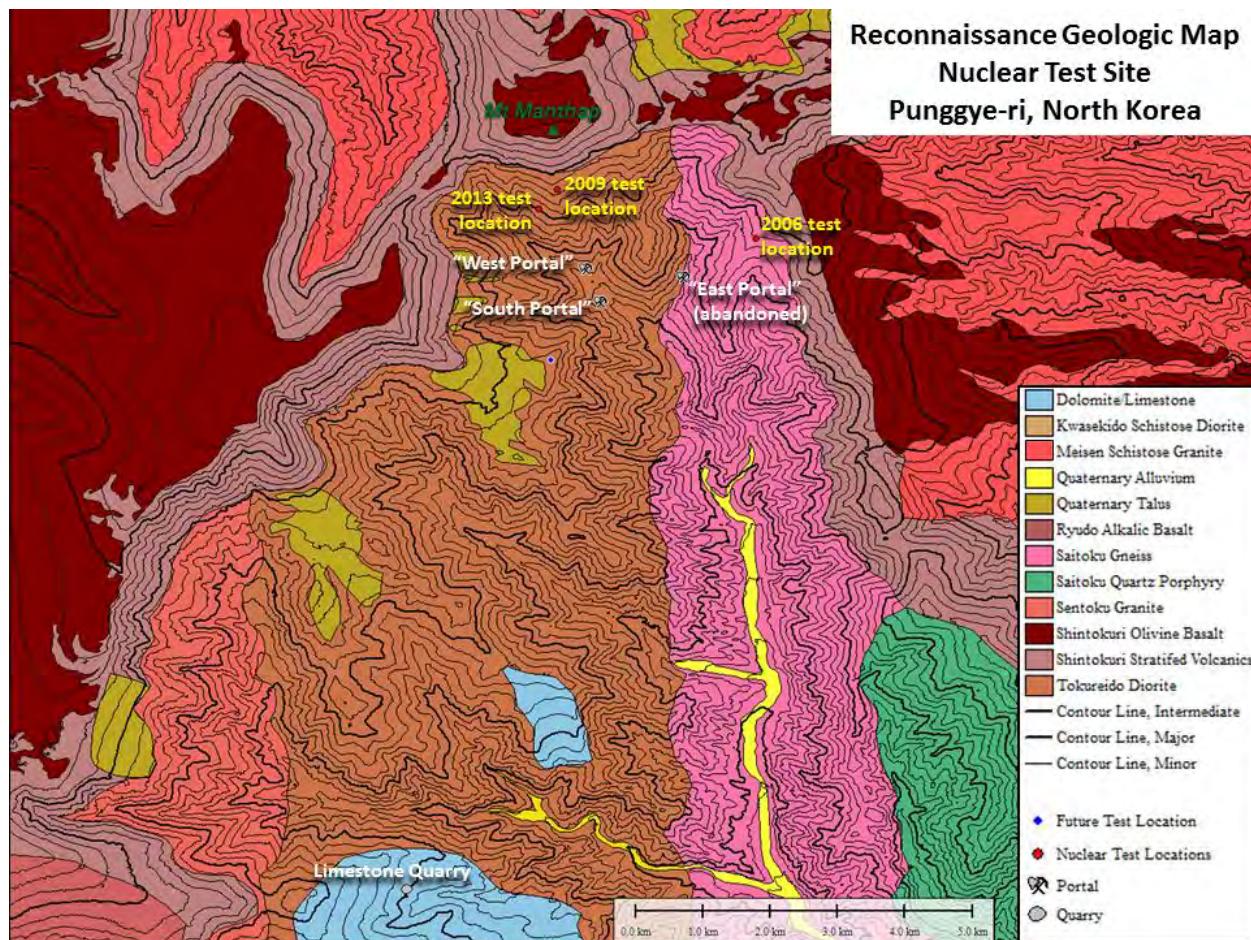


Figure 13: The derived local large scale geologic map of the Punggye-ri nuclear test site.

Lower: Small-scale reconnaissance-based USGS geologic map for comparison.

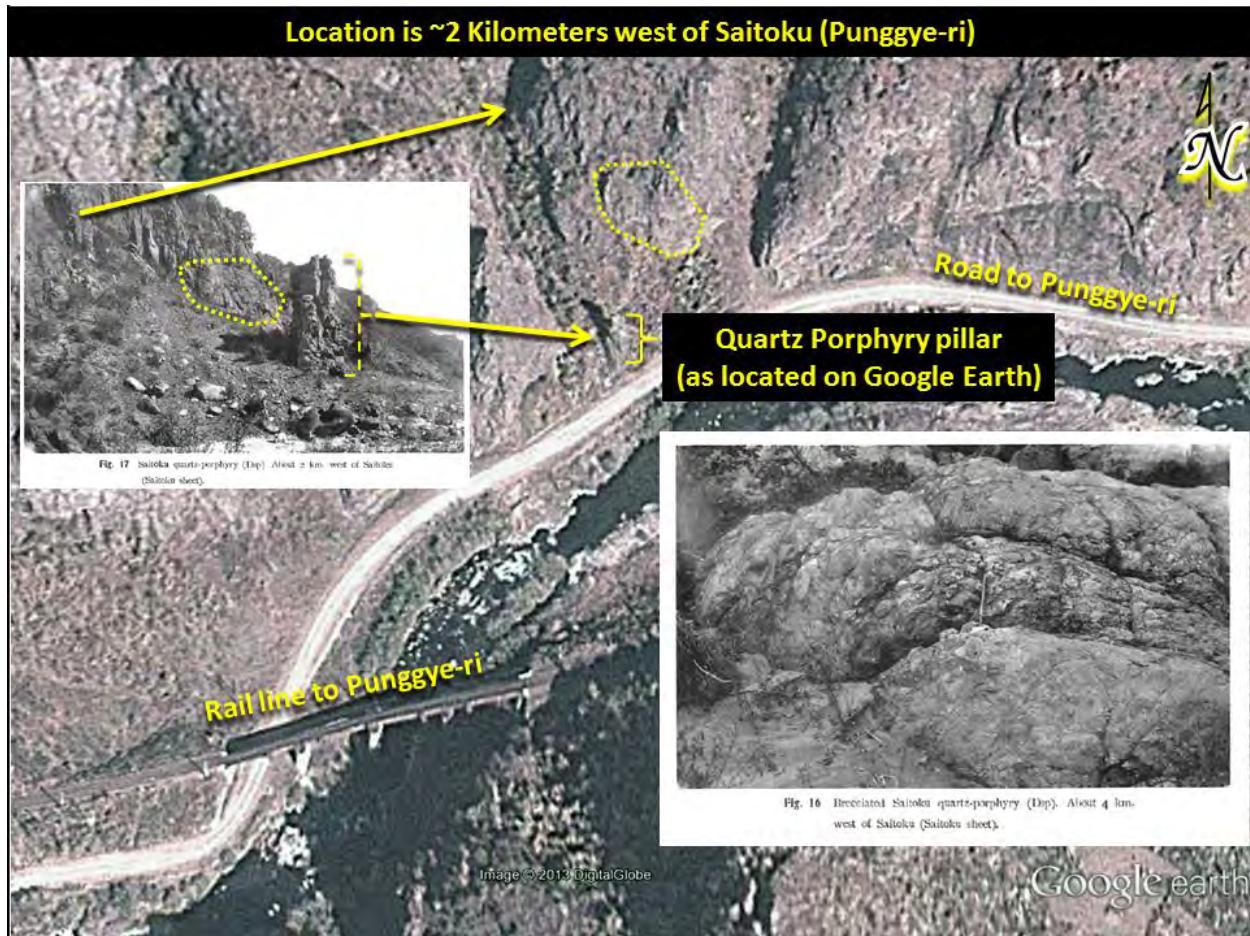


Figure 14: Ground photos of the highly fractured Saitoku quartz porphyry.

Ground photos taken circa 1932 of the highly fractured Saitoku quartz porphyry of the Cretaceous-Jurassic age. Given the location information regarding the rock pillar in the Japanese Folio #4 (2 kilometers west of Saitoku (now Punggye-ri)), it was possible to locate the rock pillar outcrop on Google Earth.

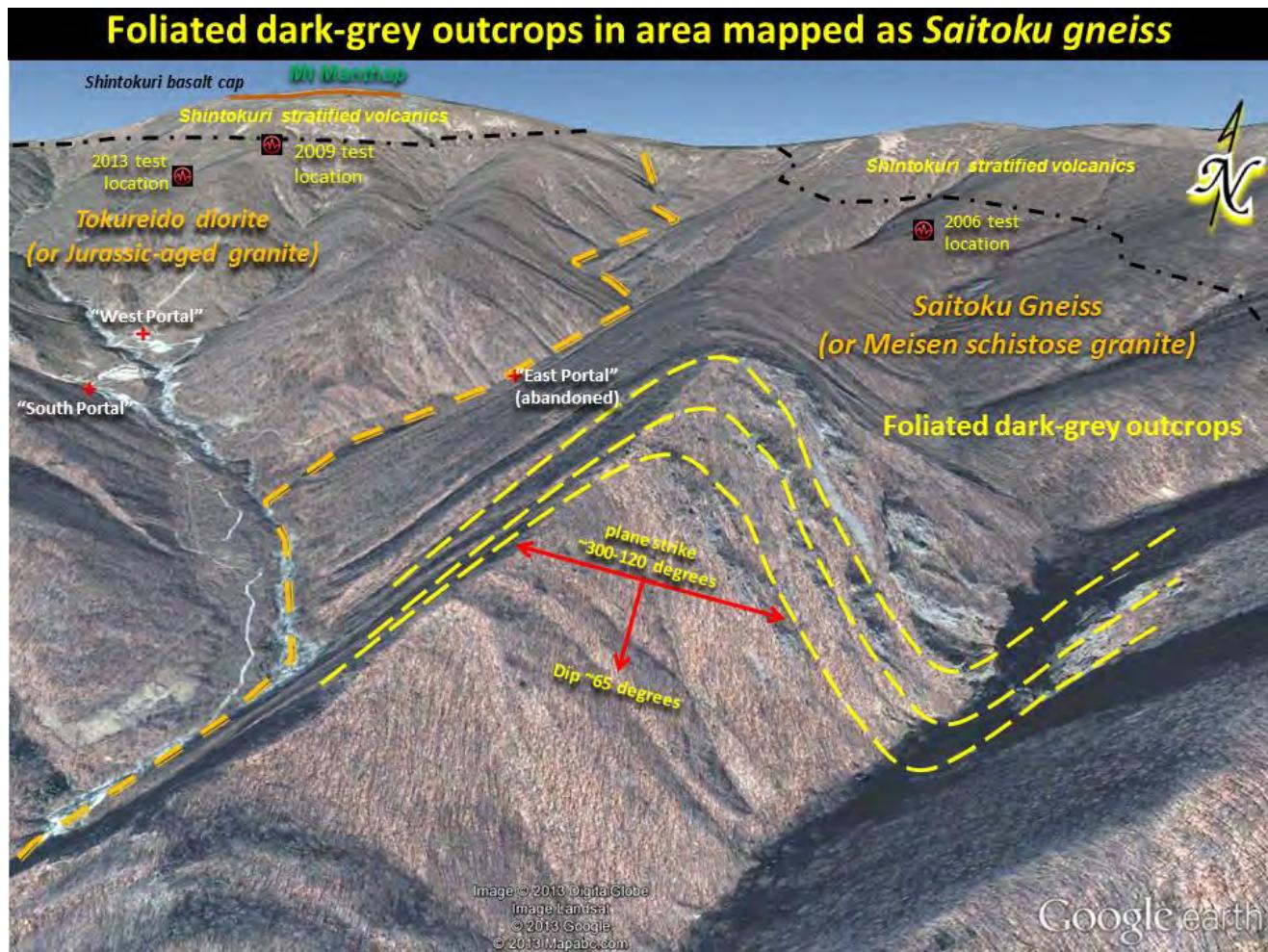


Figure 15: Google Earth overlay of the foliation patterns near the Punggye-ri nuclear test site.

Highly foliated (and likely highly fractured) outcrops along the ridge associated with North Korea's first underground nuclear test in 2006 as observed on Google Earth in 3-D perspective looking north towards Mt. Manthap. Both our mapping and that of the USGS previously identify this as Saitoku gneiss. However, a strong case can also be made for this being the “unknown age” (probably Jurassic) “Meisen schistose granite” (see discussion in text).

Similarities with *Saitoku* quartz-porphyry?

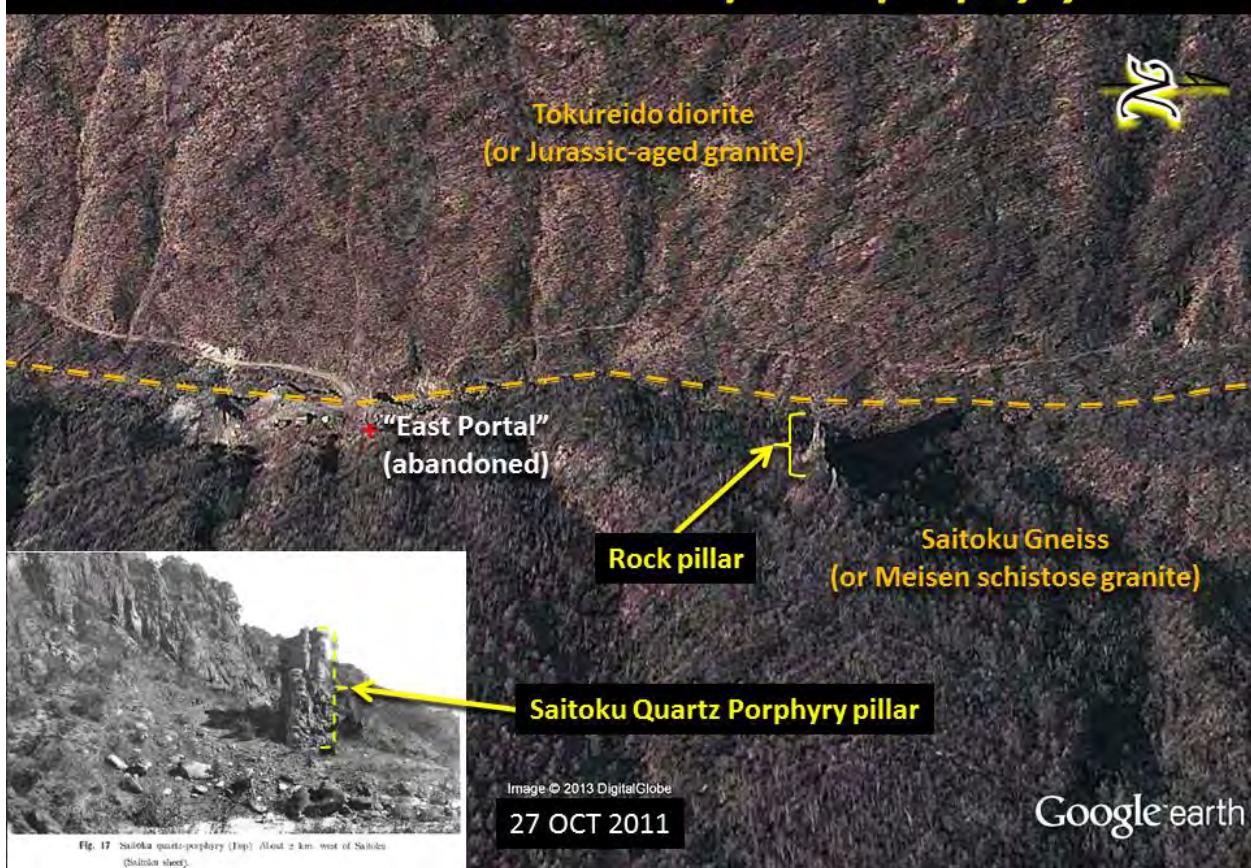


Figure 16: Google Earth image of a rock pillar in comparison with one identified in inset photograph obtained circa 1932 just west of the village of Punggye-ri .

A prominent rock pillar, not unlike the quartz porphyry pillar (shown in the inset), is located near the “East Portal.” This portal was associated with North Korea’s first underground nuclear test (in 2006). The dashed line marks and inferred lithologic boundary.

Differential Coloration and Erosion Suggest Different Underlying Lithologies

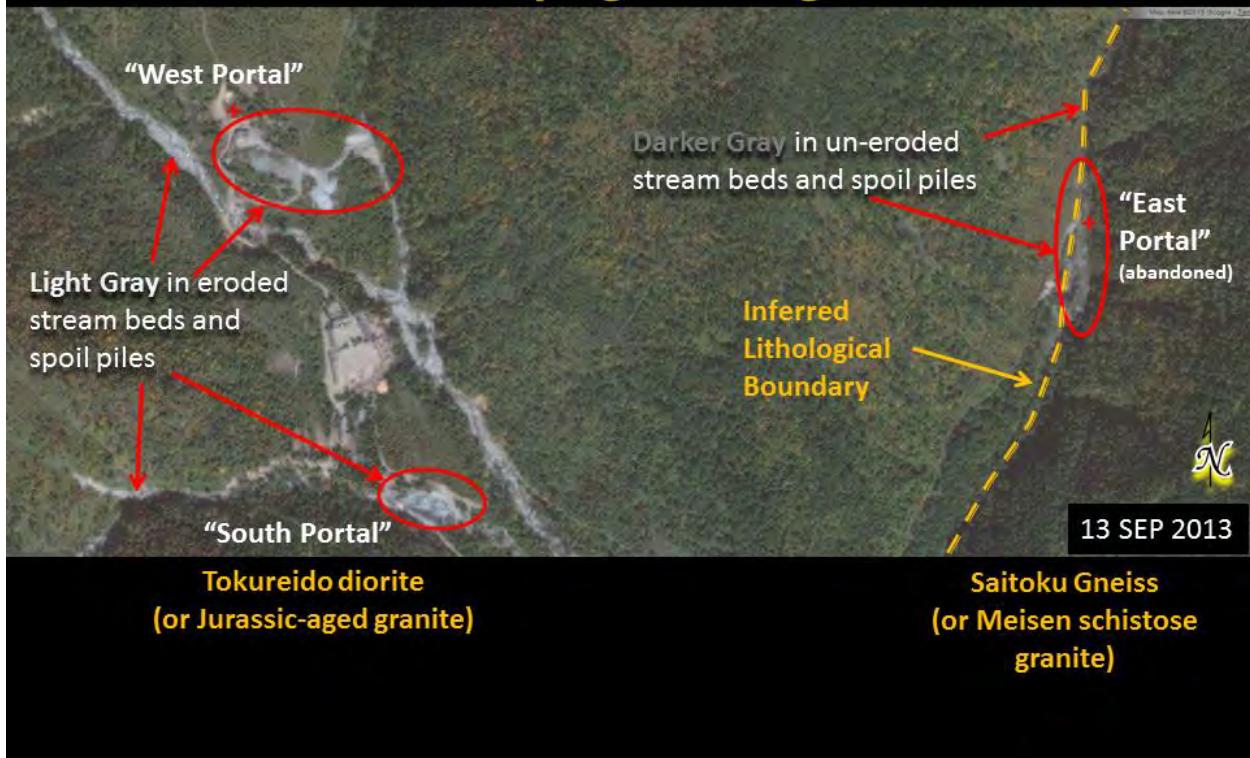


Figure 17: Differential coloration of excavated spoils at the tunneling locations of the Punggye-ri nuclear test site.

Coloration variations and differential erosion across the inferred lithological boundary provide additional evidence of different underlying host-rocks.

Discussion

Several topics of interest relevant to the North Korean Test Site can be reexamined given the results presented above.

1. Carbonate Rocks in the Vicinity of the Punggye-ri Nuclear Test Site?

This study provides an objective basis for evaluating the plausibility of dolomite/limestone units in the immediate vicinity of the 2009 nuclear test epicenter (as suggested by the results of the USGS ASTER image evaluation). Our conclusion is that there is little evidence to support the existence of such a distinct lithologic boundary bifurcating Mt. Manthap near the 2009 nuclear test event epicenter. According to Buttleman and Matzko:

"Of particular interest in the area of folio 14, located just 14 km south of the test site, is the widespread occurrence of thick carbonate rocks and the containment difficulties they present. ... The atlas series also indicates that blocks of carbonates are preserved within the granite masses as roof pendants; these pendants occur within granites mapped in all three folios, though they are relatively uncommon. Although no carbonates are shown in the immediate area of the test site on the small-scale geologic maps available, the differences in the maps suggest some uncertainty as to the extent and proximity of the carbonates to the site, and even the possibility of roof pendants within the Mesozoic (Jurassic) granites of the Mt. Manthap area. While there is presently no evidence that the nuclear test of October 2006 was conducted in carbonates, their presence may limit the locations of potential future tests in this region."

Although we have found little evidence to indicate the presence of carbonate rocks (dolomite/limestone) in the immediate vicinity of the test site proper, by employing "geomorphometrics" and visual inspection of commercial satellite imagery, we did find evidence of one likely "roof pendant" (Figure 8 and 11), which may have also served as the location of a former limestone quarry. From our analysis, together with previous USGS reporting, we found agreement with the small scale North Korean geological map from 1994 which shows the northernmost extent of a main block of dolomite/limestone is also the location of an active limestone quarry. This quarry was first identified as likely being for limestone by Chirico based on spectral analysis of ASTER multi-spectra imagery in combination with interpretation of commercial satellite electro-optical imagery in 2010.²⁶

It could also be argued that since this is the closest observed limestone quarry to the underground test site, it is unlikely that a source of limestone is present any closer to the test site proper. Limestone is an important ingredient in cement, a commonly used material either alone or mixed in concrete for reinforcing tunnel walls and/or for emplacement purposes (Pakistan was reported to have sealed its nuclear test tunnel at Ras Koh with a mixture of sand and 6,000 bags of cement in 1998)²⁷. If such a source of limestone were readily accessible closer to the test site, then it would likely have been tapped to limit transportation costs in terms of time, distance, and diesel truck fuel.

2. Rock Type at the North Korean Underground Nuclear Test Site

In assessing the regional geologic setting, Buttleman and Matzko point out:

*"In general, low porosity, dense, massive rocks such as granite...offer good environments for underground nuclear tests. The tectonic history of this area suggests, however, that rocks pre-dating the Mesozoic Songnim movement have suffered deformation from this movement, and are folded, sheared, and fractured, thus reducing the integrity of the rocks. The ground photographs provided in the atlas suggest that many rocks, including those post-dating the Songnim tectonic movement, might be highly fractured and thus complicate containment, and require adequate technical remediation."*²⁸

Murphy, et al., 2013, similarly put it this way,

"Little information is available from published sources on specific details of the rock types and their properties in the vicinity of the NK test site. Smaller scale geologic maps...for the Korean peninsula indicate the presence of Achaean (3950-22500 Ma) (millions of years ago) and other Precambrian (>540 Ma) basement rocks in the general vicinity of the test site along with Mesozoic (Jurassic-Triassic, 250-145 Ma) intrusive igneous rocks , as well as Cenozoic and Quaternary (<2.5 Ma) (extrusive volcanic rocks extending toward the test site area from Mount Changbai and adjacent areas to the northwest (Steinshouer et al., 1997). Best estimates indicate that most rocks in the NK test site area are low-porosity, dense, intrusive and extrusive igneous rocks, including granites (considered the most likely source rock), basalts, and rhyolites, which are Mesozoic or younger. These are viewed as providing the best environment for containing nuclear explosion tests; rocks older than Mesozoic tend to be more fractured and less competent. Thus, the surface rock types identified from the

limited available literature sources for the NK test site area suggest competent hard rocks, consistent with the inference that the nuclear tests were conducted in “good coupling” media.²⁹

Our analysis identifies evidence of potentially highly fractured rock near the “East Portal.” A comparison of available ground photos of the highly fractured Saitoku quartz porphyry near the village of Punggye-ri with outcrops in the eastern portion of the test site is made possible with commercial satellite imagery as is available on Google Earth (Figure 12, Figure 13, and Figure 14). The rocks in the eastern portion of the nuclear test site proper are exposed as highly foliated and broken outcrops and thus also likely highly fractured, and the foliations are somewhat consistent with a description for the “Meisen schistose granite”.³⁰

Based on reporting by the Japanese geologist, Iwao Tateiwa, the Meisen schistose granite is part of the regional intrusive basement system described as being of unknown age (but labeled by others as Mesozoic/Jurassic). Tateiwa described these rocks in some places as having been “intensely pressed” and that the “strike and dip of their schistosity plane, which is obviously of the pre-Tertiary, are variable as shown in the geologic maps. Overall, these planes strike NW-SE and dip sharply to the northeast or nearly vertical.” This orientation is consistent with the foliations observed in the outcrops in the eastern portion of the Punggye-ri nuclear test site, as visible on Google Earth, which also strike NW-SE (~300-120 degrees) and also dip steeply (~65 degrees), albeit to the southwest.

While the lithology of the eastern portion of the Punggye-ri underground nuclear test site is expressed in highly foliated rock outcrops and at least one prominent rock pillar, the western portion is more subdued with somewhat more rounded slopes with a less angular dendritic stream pattern more indicative of a non-foliated granite or diorite. When we view the test area in the vicinity of the tunnel portals, another possible indicator of lithological differences appears across the inferred geologic boundary. Figure 16 at least suggests that the host rock that has been excavated from the “East Portal” is somewhat darker grey than the excavated host rock from either the “West Portal” or the “South Portal” which appear to be lighter grey in color.

Such potential differences in lithology between the host rock accessible via the “West Portal” and that accessible via the “East Portal” may also help to explain why the “East Portal” has been abandoned. That the “East Portal” has indeed been abandoned is evidenced by the removal of all but two buildings outside the portal³¹, the lack of any vehicular track activity, and most importantly, that no road or bridge repair work of any

kind has been observed following the heavy flooding of the test site in the summer of 2012. Contrariwise, such repair work has been regularly observed at both the “West” and “South” portals, with mining and vehicular activity ongoing in association with those portals.

3. Containment Factors Associated with North Korean Underground Nuclear Testing

A number of factors may provide insights as to why the first test in 2006 (associated with the “East Portal”) vented detectable radioactivity in the form of noble gases, while the subsequent two tests in 2009 and 2013 (associated with the “West Portal”) did not (apart from human post-test activity, see reference 5 and Figure).

These factors could include:

- 1) That the 2006 test was emplaced at a location affording less overburden, hence shallower depth of burial than the following tests and hence closer to the surface to facilitate easier gas migration.³²
- 2) Higher yield tests (e.g., 2009 and 2013), are more likely to produce “containment stress cages” than the lowest yield test of 2006.³³
- 3) The detection of radionuclides could have simply been a spurious detection unrelated to the 2006 test.
- 4) The geology of the host rock used for the 2006 test was less competent than that used for the 2009 and 2013 tests (supported in part by the geomorphological analyses in this study).
- 5) The North Koreans may have employed more robust containment strategies for the post-2006 tests (as the North Koreans apparently claim in an animation video publicly broadcast in 2010, see and Figure 19 and Figure 20).

Re-Entry of West Portal is a Candidate Cause of Radionuclide Release in April 2013



Figure 3. Tunneling activity well underway.
Return to the article: New Tunneling Activity at the North Korean Nuclear Test Site

Figure 18: Evidence of new tunneling activity.

New tunneling activity at the “West Portal” as first reported by 38North <http://38north.org/2013/06/punggye062413/>. This figure is adapted and updated from that reporting. The “West Portal” has been determined to have been used to support both the 25 May 2009 and 12 February 2013 DPRK underground nuclear tests. The left hand image is from 13 May 2013 and the right hand is from 15 October 2013. Together they show a substantial increase in excavated spoil material from ongoing tunneling activities following the 2013 test and could explain the detection of radionuclides 55 days following that event. (See Ref. 5)

Test Tunnel Layout Comparison Reveals 3 Passive Containment Features (Two of which were publicly described as being used by Pakistan in 1998)

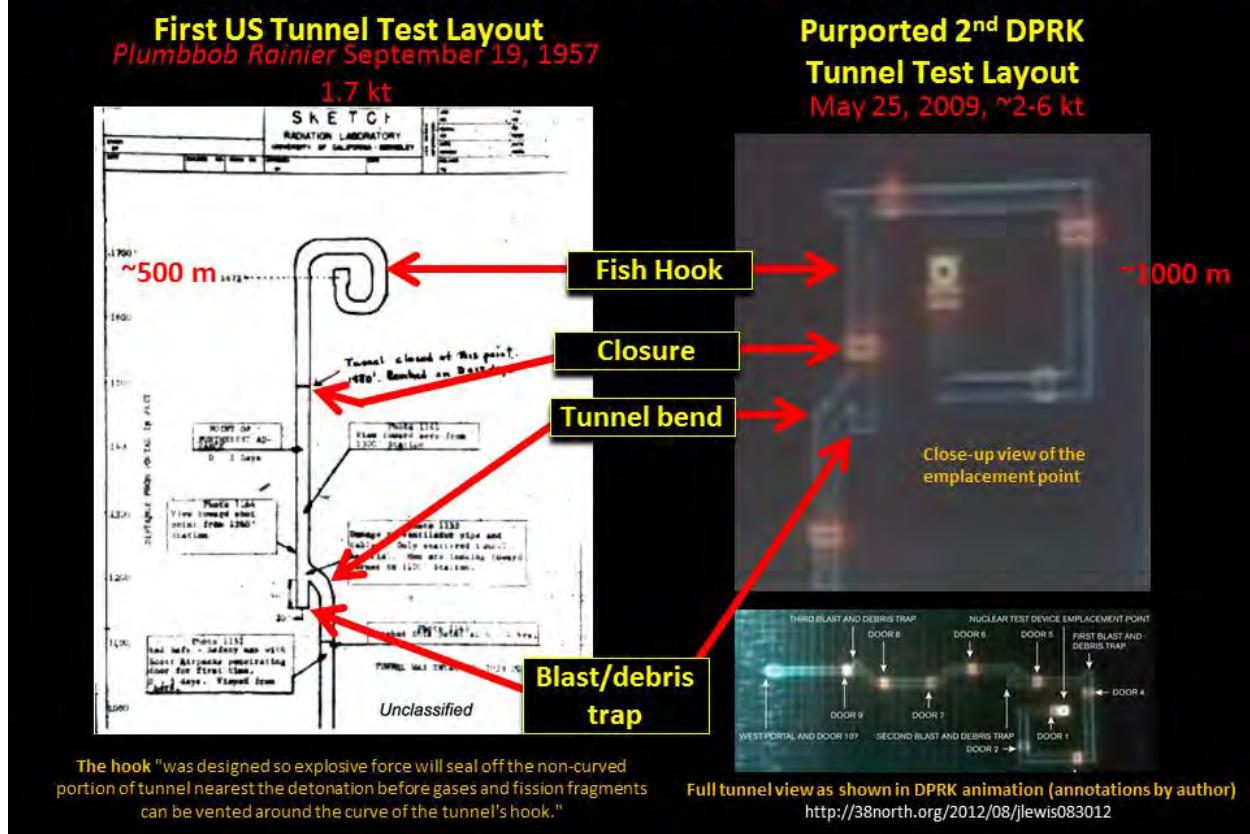


Figure 19: Schematic of possible containment design.

A North Korean broadcast video animation screen-shot, showing a purported tunnel layout of the 2009 tunnel test (right) showing that it is comparable to that of the first US underground nuclear test tunnel layout for the “Plumbbob Rainier” experiment in 1957 (left). The DPRK animation layout is plausible, and it employs three different passive containment features, two of which were described as having been used by Pakistan in its 1998 testing. The original video frames did not have annotations. Those were added by Pabian and Hecker in 2012. The North Korean video also showed the use of 10 remotely operated doors for active closure (unlikely), while the US used unspecified closures for additional blast mitigation.

Conjectural Tunnel Layout Accommodating Two Tests



Figure 20: Conjectural surface projection of a tunnel layout incorporating containment strategy per DPRK broadcast animation video. Gibbons/NORSAR relative location plot was anchored to Pabian/Hecker 2009 event location.

This conjectural design for tunnel layout from the “West Portal” to achieve containment is consistent with relative location identifications and purported tunnel plot for the 2009 test. As of this writing, a third drift is evidently being excavated via the “West Portal” in preparation for another future test.

4. The Presence of Ground Water Onsite.

There is a dearth of specific reporting on the ground water, water table depths, and rock saturation in the vicinity of the Punggye-ri nuclear test. However, surface water can be regularly observed in the streambeds throughout the test site proper, and, more importantly, water is now apparently flowing consistently from the “South Portal” (see Figure 21). To our knowledge, no water has ever been observed in the vicinity of the “West Portal” (the location of both the 2009 and 2013 tests and where new tunneling is also now underway) and it is unclear if water has ever been visible near the “East Portal” (associated with the 2006 test) in the past.

Evidence of water emanating from the “South Portal”

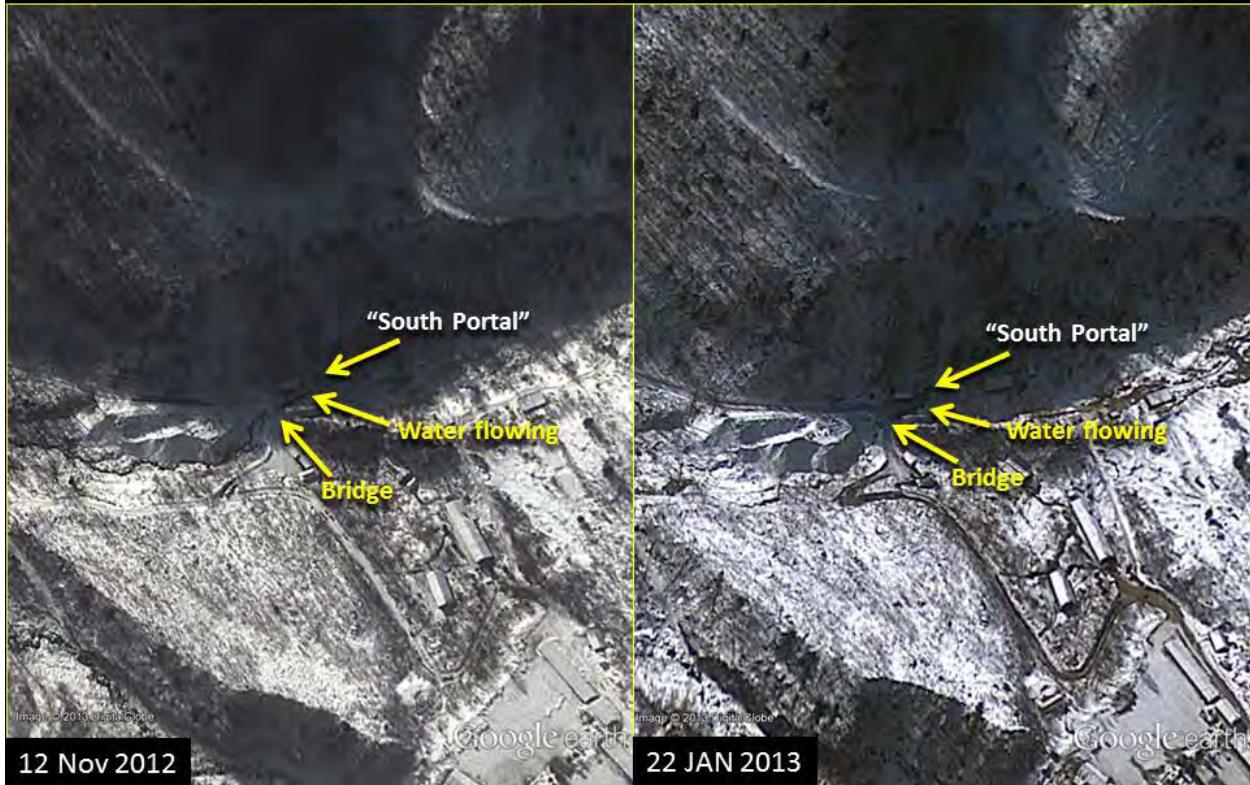


Figure 21: Evidence of water at the South Portal at the Punggye-ri nuclear test site.

Water is evidently regularly flowing out of the tunnel associated with the “South Portal.”

5. Structural Cross Sections

Figure 22 and **Figure 23** provide two simplified cross-section views of the Punggye-ri underground nuclear test site, from south to north, and west to east respectively. The cross sections illustrate the general geologic setting of the Test Site which is characterized by basaltic and volcanic rocks unconformably overlaying batholithic basement bedrock.

6. A Comment on Generating Geologic Framework Models for Denied-Access Sites

This study illustrates the procedure for generating and refining the surface geologic map for a denied-access site. This information is critical for constraining information used for a 3-D Geologic Framework Model (GFM) which extends the geologic information into the subsurface. The GFM provides a structural framework populated with subsurface physical properties and forms the basis for both near- and far-field modeling efforts. The procedures discussed in this study for refining and modifying the surface geologic map illustrates the need for an expert analyst to provide interpretation of the data and develop plausible geologic relationships. The goal of developing a “push button” methodology for generating surface geologic maps from which a GFM could be derived remains elusive.

7. Additional Spectral Analysis Work

An opportunity exists to acquire and evaluate more current, post-flooding 14-band ASTER or 220-band HYPERION imagery (or 29-Band WorldView-3, after next year’s launch), preferably in early spring, post-snowmelt and pre-foliage, and to specifically focus on those areas of newly exposed bedrock (and newly excavated tunnel spoil) to cross-check our findings with the ASTER spectral geologic library. Such imagery is not yet available as of this writing (but has been requested via the USGS).

8. Additional Applications for Synthetic Aperture Radar Imagery

The application of commercially available high resolution synthetic aperture radar (SAR) imagery could also help to shed new light on the underlying lithologies and the extent of foliations and fracturing, and, if both pre- and post- test radar imagery for each event (including any future events) could be obtained, interferometric coherent change detection would likely also reveal subtle surface disturbances yielding even greater precision with respect to the event geo-locations.

Conclusions

This study provides a revised reconnaissance-based geologic map, site characterization, and geologic report for the area surrounding the underground nuclear test site near Punggye-ri, North Korea. Our research involved a reevaluation of all available geologic information combined with original analysis of commercial-satellite-sourced remote sensing data to derive a more accurate understanding utilizing a novel integrated “geomorphometric” approach.

The results indicate that the North Korean nuclear test site is located in Mesozoic/Jurassic age granitic-like basement rock, similar to that mapped on a small-scale North Korean geology map published in 1994. However, our findings also show that there is reason to believe that this basement host rock may vary in competency, with the 2006 event most likely having occurred in less competent, e.g., fractured, host rock (either Precambrian Saitoku gneiss (as mapped) or Jurassic-age Meisen formation’s schistose granite), while the subsequent 2009 and 2013 tests more likely occurred in a more competent host rock (either Cretaceous Tokureido diorite or less fractured Mesozoic-age granite) thereby providing better containment and better coupling. Such information offers a new basis for understanding possible radionuclide venting mechanisms for the 2006 test, as compared to the higher yield 2009 test that did not leak detectable radioactivity, while also helping to provide insights on the cause of subsequent abandonment of the “East Portal,” which had been used to support of the 2006 test.

We also found that there is a low probability for the existence of Precambrian (Proterozoic, “Matenrei”) limestone/dolomite in the immediate vicinity of the nuclear test site, which thus mitigates the likelihood of prompt venting due to non-condensable carbon dioxide gas generation as a result of any future nuclear testing in the area. This study is the first to address these issues specific to the absolute event locations associated with North Korean nuclear testing at the Punggye-ri Nuclear Test Site.

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The opinion(s) expressed in this report are the authors' alone and do not necessarily represent those of Los Alamos National Security, LLC., the Los Alamos National Laboratory, the U.S. Department of Energy, the U.S. Department of State, or any US Government entity.

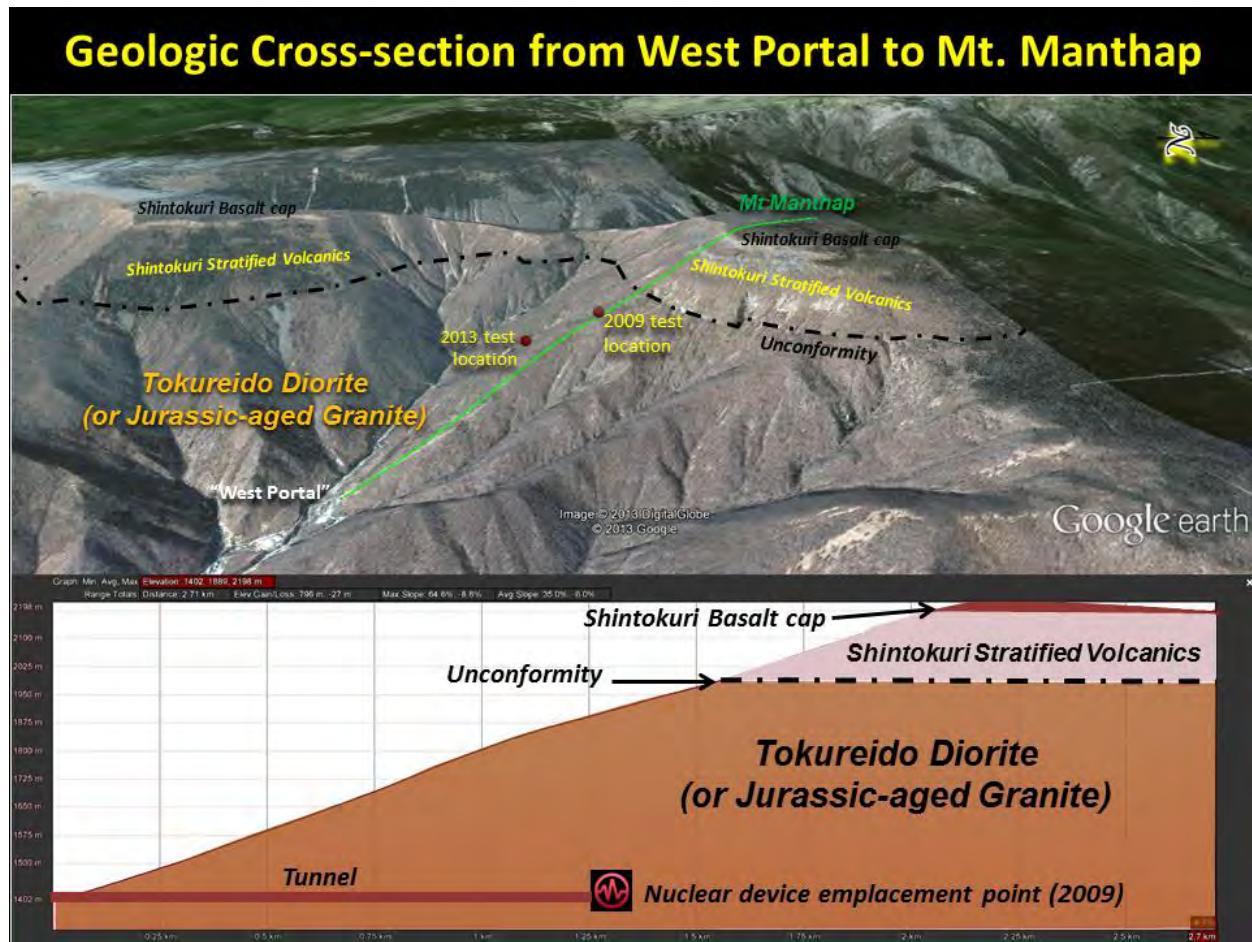


Figure 22: South-North Geologic Cross-section of the Punggye-ri Nuclear Test Site from the "West Portal" to Mt. Manthap

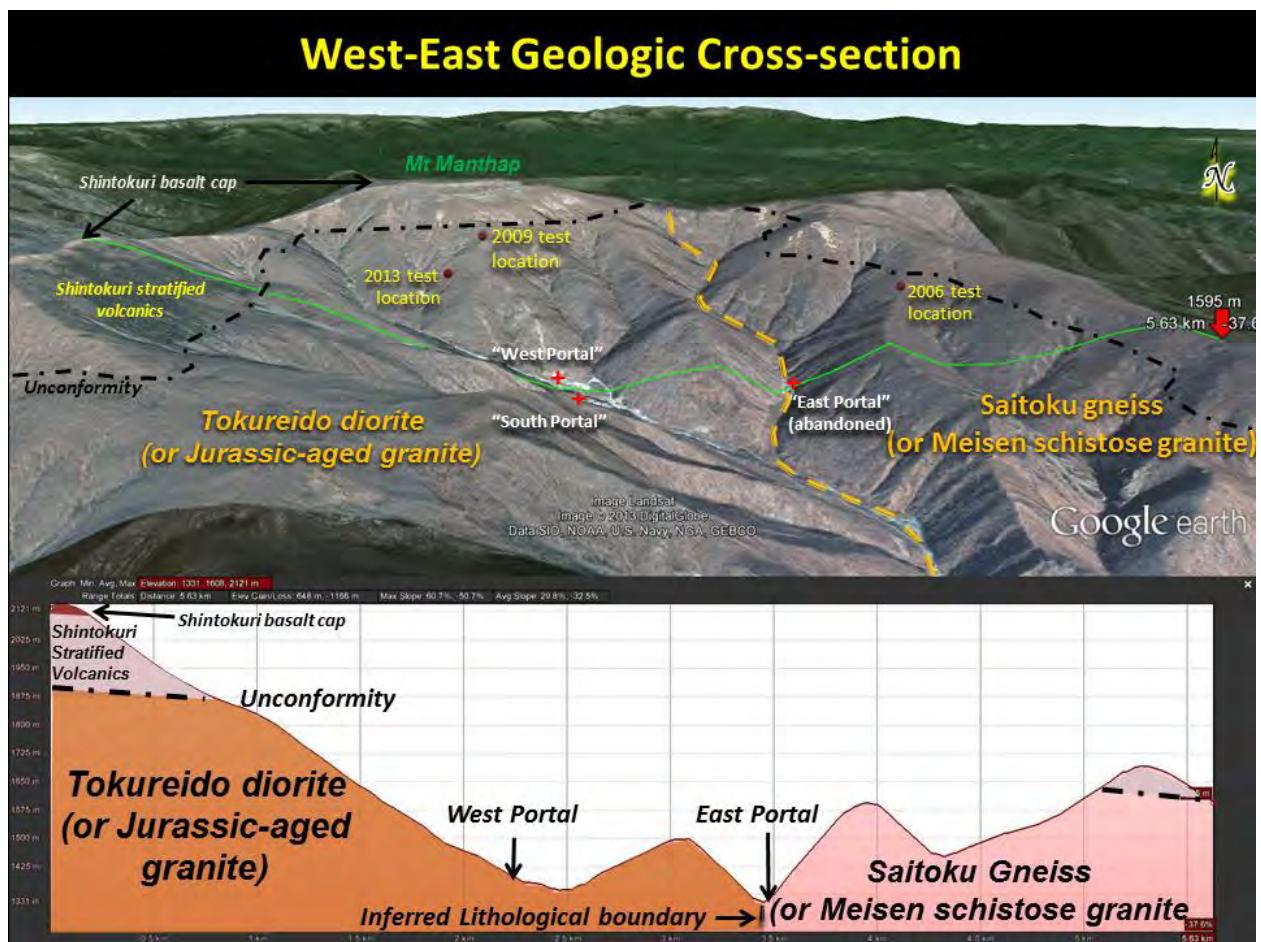


Figure 23: West-East Geologic Cross-section of the Punggye-ri Nuclear Test Site.

Appendix A: Geo-location of North Korean Nuclear Tests

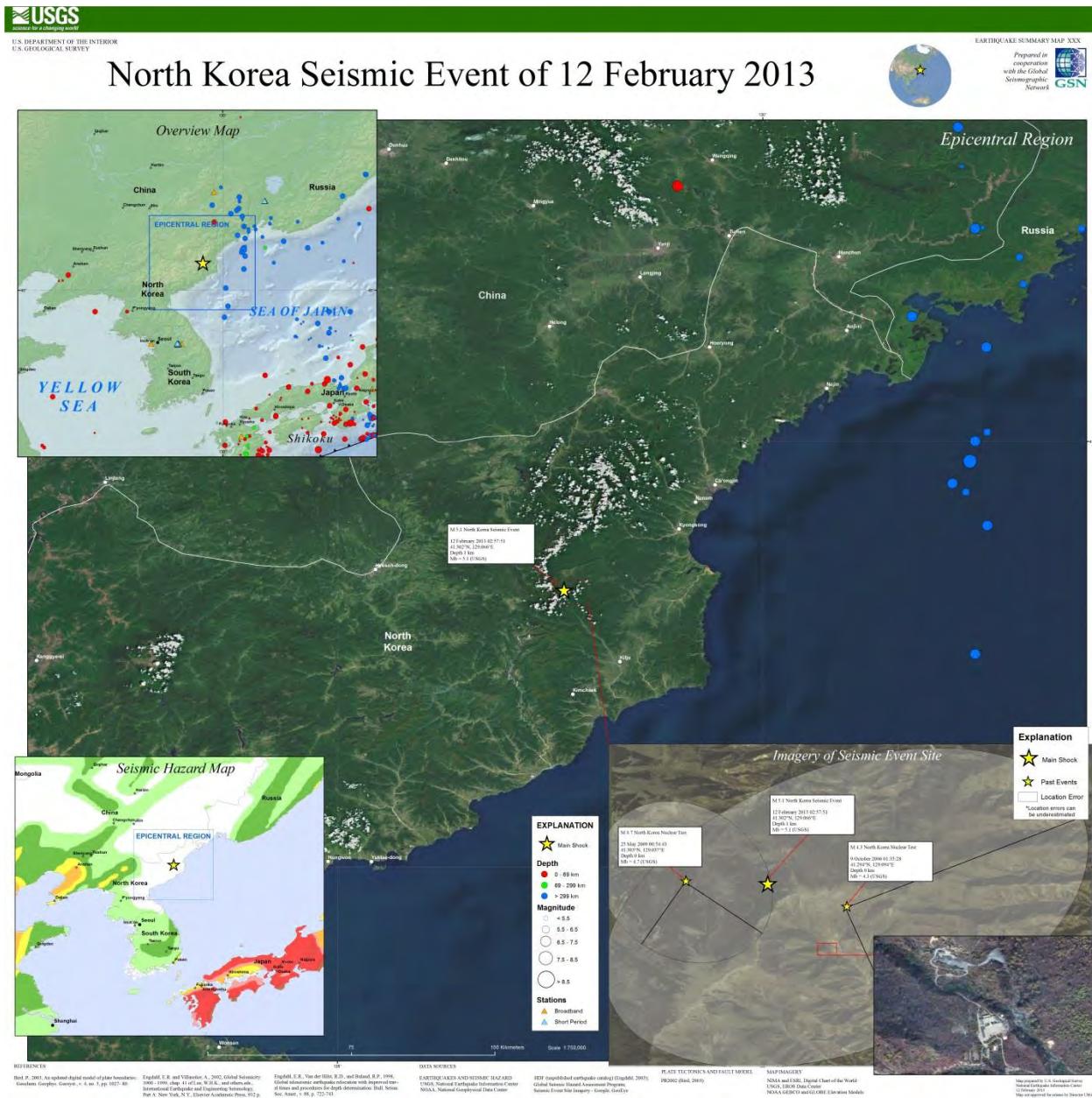


Figure A-1. USGS seismically derived locations (without application of relative location via differential waveform interferometry). The “West Portal” is shown at lower right.

Source: <http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2013/NorthKorea.jpg>

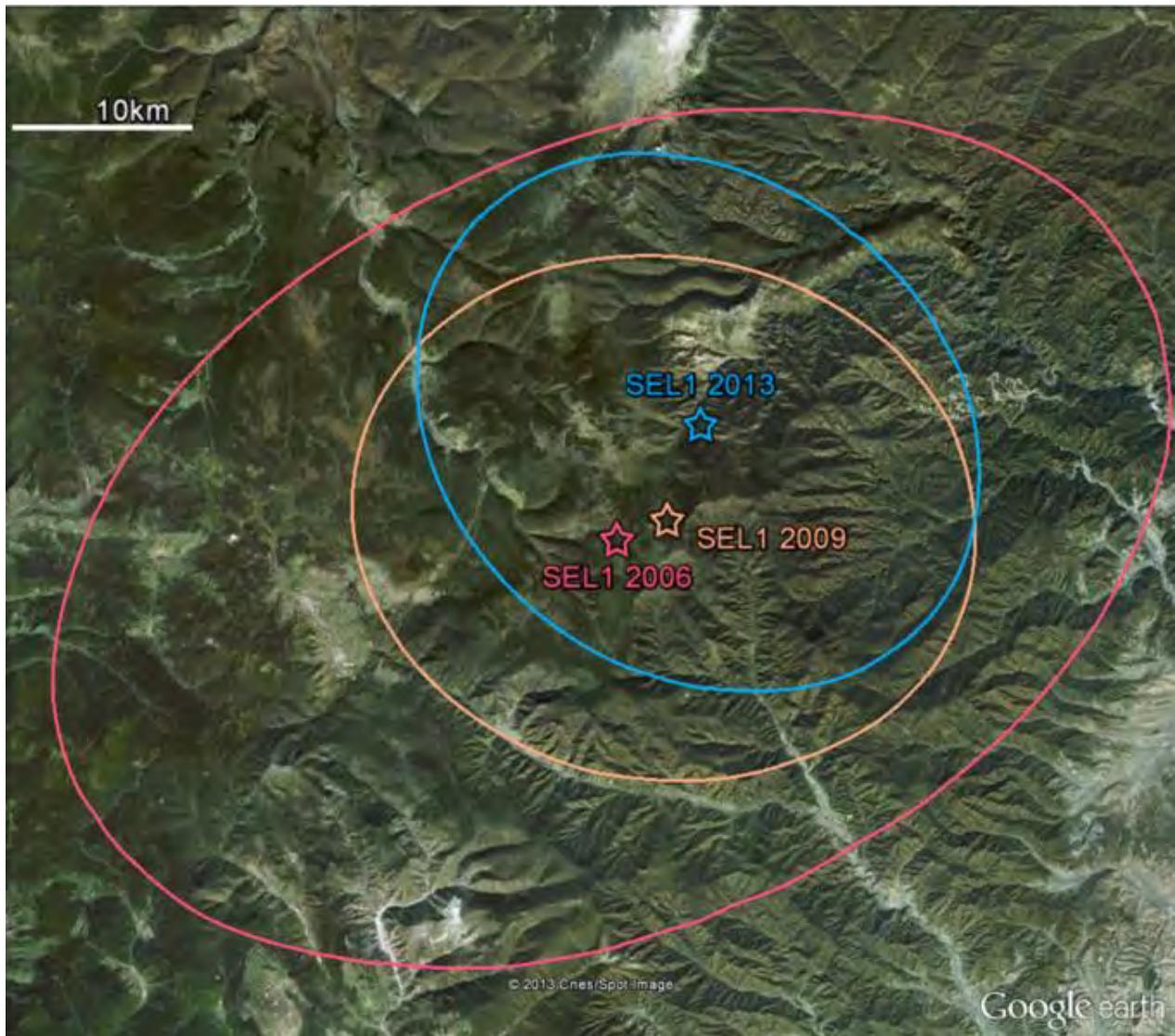


Figure A-2. CTBTO seismically derived locations (without application of relative location via differential waveform interferometry).

Source: <http://www.ctbto.org/press-centre/press-releases/2013/on-the-ctbtos-detection-in-north-korea/>

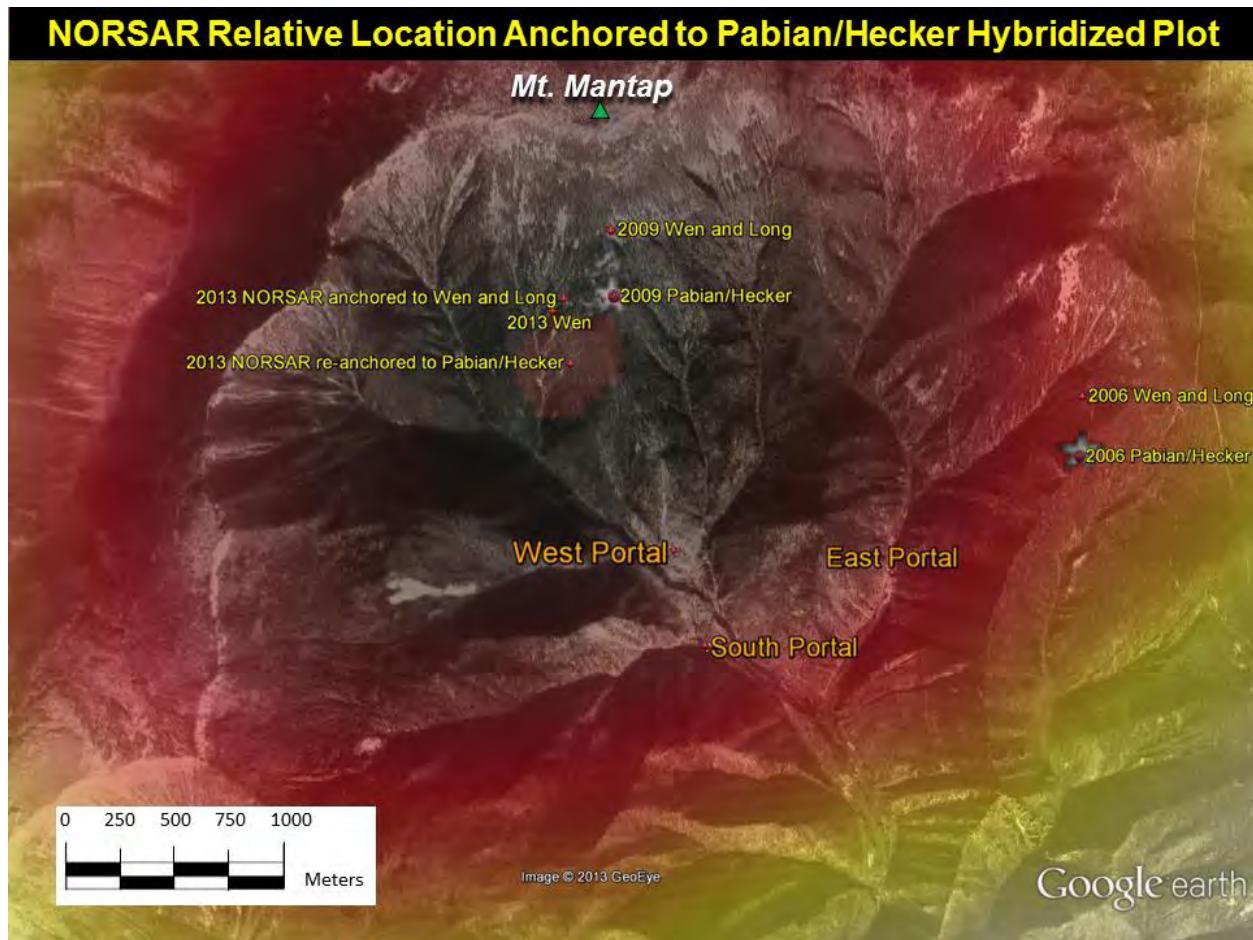


Figure A-3. Absolute locations as derived through combination of differential waveform interferometry plots with commercial satellite imagery of test tunnel portals and topography. Colored relative location plot created by Steven Gibbons/NORSAR (and originally anchored to Wen and Long derived test locations) but anchored here to Pabian/Hecker derived test locations, and overlain on Google Earth. (Note that the absolute locations as determined independently by Wen/Long and Pabian/Hecker are within 300 meters of each other)

Source:

http://www.academia.edu/4943283/Detection_and_Location_of_the_February_12_2013_Announced_Nuclear_Test_in_North_Korea

Appendix B: Folio # 4 Geology Summary (e.g., Meisen) and Key Graphics

(i)

EXPLANATION OF GEOLOGY⁽¹⁾

by Iwao Tateiwa.

The Meisen district or the area embraced in the geological maps of this Atlas occupies a southern part of N. Kankyo-Dō, covering about 1491 square kilometres, bounded on the east by the Sea of Japan and on the south by the Kisshū district, studied and mapped by Mr. F. Yamazaki.⁽²⁾ The longitudes 129° 30' E. and the latitude 41° 10' N. intersect at the center of the district.

No important reference to the geology of this district is found.

Topographically the Meisen district can be divisible into three more or less markedly characterized belts, trending in general N25E. approximately, viz. the coastal mountainous belt, the central hilly belt and the western mountainous belt.

The Coastal mountainous belt consists mainly of schistose granites, intruded and underlaid, in the southern part of it, by various types of the Tertiary alkalic rocks. In the central hilly belt, are widely distributed the Cainozoic strata, resting on the schistose granites and accompanied by a large amount of volcanic rocks. The belt ascends to the east abruptly to the coastal mountainous belt, the boundary between these two belts being originated in a great fault (fault No. XI) running N25E. To the west, however, it becomes higher gradually in relief and pass into the western mountainous belt, constructed essentially of schistose granites.

All rocks seen in the present district are classified as in the following synopsis:

1. Basemental system
unconformity
2. Tertiary system
Ryūdō group
unconformity
Meisen group
unconformity
Shichihōsan group
unknown relation
Gengen group
unconformity
3. Quaternary system
Pleistocene series
unconformity
Recent series
4. Intrusive rocks of unknown relation

BASEMENTAL SYSTEM.

The Basemental system in the present district is represented by granites more or less schistose. So far as the mineralogical compositions are concerned they are divided into biotite-granite and biotite-hornblende-granite, of these the former is again divisible into at least two, viz. a nonporphyritic or slightly porphyritic one and a conspicuously porphyritic one with larger distinct phenocrysts of alkalic feldspar. We do not know decidedly, however, whether they are differentiated phases of a batholith, or are of different periods of invasion. In some places distinctly porphyritic biotite-granite is seen intensely pressed showing typical "augen" structure.

They inclose frequently masses of crystalline limestone, arenaceous rock and more or less melanocratic diorite as well as granitic rocks.

Strike and dip of their schistosity plane, which is obviously of the pre-Tertiary, are variable as shown in the geological maps. Generally to say, however, it strikes N.W.-S.E. and dips steeply to the northeast or nearly vertical.

Concerning the geological age of this system we have no satisfactory date to suggest it definitely, though it is highly probable, thinking from the lithological nature, that the biotite-granite which is not distinctly porphyritic and is extensively distributed in this district, belongs to the so-called red granite intruding into the rocks of Mach'omonyong series in the various parts of the adjacent region of the present district and considered to be older than the Cambrian.⁽³⁾

TERTIARY SYSTEM.

Ryūdō group. The lowest division of the Tertiary system, namely the Ryūdō group, is distributed widely in the western part of the central hilly belt, and comprises shale, sandstone, coal, etc., accompanied by a large amount of alkalic basalt. The plant remains richly yielded from the lower division of this group warrants the Lower Tertiary age of this group. It is classified into two formations enumerated from the lower as follows:

- a. Ryūdō formation.
- b. Ryūdō alkalic basalt.

a. Ryūdō formation consists of shale, sandstone, conglomerate, coal, etc. resting on the eroded surface of schistose granites of the preceding system, mainly in the western part of the central hilly belt. They are continental accumulations formed probably in a shallow fresh or brackish water, and attain as a whole about 80 metres in thickness. Numerous remains of plant, preserved fairly well, have been yielded from a light brown shale at various places in the tract of this formation. Of these following 16 species are recognized by the writer as important:

<i>Pinus heptia</i> (Ung.)	<i>P. palaeostrobus</i> Ett.
<i>Glyptostrobus europaeus</i> (Brongn.)	<i>Sequoia langsdorffii</i> (Brongn.)
<i>Juglans nigra</i> Heer.	<i>Betula brongniartii</i> Ett.
<i>Carpinus grandis</i> Ung.	<i>Alnus kefersteinii</i> (Goep.)
<i>Fagus antipoda</i> Heer.	<i>Castanea kuvinyii</i> Kov.
<i>Quercus furcinervis</i> Ung.	<i>Ulmus braunii</i> Heer.
<i>U. cf. elegans</i> Nath.	<i>U. cf. longifolia</i> Ung.
<i>Planera ungeri</i> Ett.	<i>Prunus cf. serrulata</i> Heer.

The Ryūdō flora as shown in the above list is no doubt closely related to the so-called "Arctic Miocene" and may not be younger than the Chōki flora which is essentially of Arctic Miocene plants commingled with some forms closely allied or identical to some existing plants and has been tentatively considered to be of the Oligocene.⁽⁴⁾

b. Ryūdō alkalic basalt covers concordantly the preceding strata and consists mainly of numerous sheets of tephritic? trachy-basalt accompanied by a small amount of leucite-basalt, tuff, conglomerate, tufaceous sandstone, shale, etc., accumulation of them attaining in some places more than one thousand metres in thickness. It is suggested from the field study that the vicinity of Onsuhei, four kilometres south of Kotendo, where the formation embraces comparatively large amount of tuff and conglomerate together with dykes of the same character with most sheets of this formation, was the center of eruption of lavas at this time if not all the lavas belonging to this formation are considered to have been poured out from the supposed center.

The leucite-basalt occurs as effusive? sheets resting directly upon the preceding coal-bearing strata, underlaid by sheets of the tephritic? trachy-basalt and associated with its conglomeratic

tuff, at Ryūdō four kilometres northwest of Meisen. It is the second occurrence of leucite rock in Eastern Asia north of the Philippine Islands, the first being that of Utsuryōtō Island⁽⁵⁾ in the Sea of Japan.

Meisen Group. After the period of eruption of the enormous amount of the Ryūdō basalt the present district became land and was eroded to a certain degree but before long abrupt subsidence took place and was invaded by sea water, in which the second division of the Tertiary system, the Meisen group, was formed. It consists of a series of conglomerate, sandstone, shale, coal, etc. reaching about 1800 metres in the entire thickness, accompanied by flows and intrusive bodies of olivine-basalt, and can be differentiated into three formations which pass lithologically into one another. They are nearly restricted in their distribution in the central hilly belt. Their geological structure and lithological natures, together with their geographical distribution, seem to suggest that the shallow sea, where the rocks of this group were deposited, was bounded by land at least to the west and the east.

Paleontological study of a flora yielded from the middle horizon of this group seems to show also the Lower Tertiary age of this group.

The three formations enumerated from the oldest are as follows:

- a. Heirokulō formation.
- b. Kanchindō formation.
- c. Mankodō formation.

a. Heirokulō formation consists largely of cross-bedded conglomerate and sandstone, with numerous remains of marine molluscs, and attains about 600 metres in the entire thickness. Rarely local unconformity is recognized in the formation itself.

b. Kanchindō formation consists essentially of light brown shale with abundant plant and animal remains, intercalating thin layers of sandstone and marly nodules, and is measured about 200 metres in thickness at the most part. Important plants determined by the writer from the shale are as follows:

Glyptostrobus europaeus (Brongn.)	
Sequoia langsdorffii (Brongn.)	Araucaria sp.
Dryostrobus ? sternbergii (Goep.)	
Pterocarya cf. denticulata (Web.)	
Juglans nigra Heer.	Carya serratifolia (Goep.)
Betula cf. ermanii Cham.	Fagus ferruginea Ait.
Carpinus grandis Ung.	Quercus sp.
Quercus cf. pseudocastanea Goep.	Planera ungeri Ett.
Populus gaudini F. O.	P. cf. zadlachi Heer.
Hamameris cf. japonica Sieb. et Zucc.	
Tilia cordata Mill.	Acer pictum Thunbg.
A. palmatum Thunbg.	Triptaleja cf. almqvistii Nath.

The Meisen flora listed just above seems to contain more percentage of plants no doubt closely related or identical to those living than it is the case in the flora of Chōki series. The abundant occurrence of American beech (*Fagus ferruginea* Ait.) which is very common in the post-Miocene flora of Japan,⁽⁶⁾ seems to be especially noteworthy. But, considering from the general composition of the flora, it can hardly be of the Upper Tertiary, for, so far as their general composition and the climatic condition indicated by them are concerned, the Meisen flora approaches very near, and is no doubt closely related in age, to the South Korean Chōki flora but differs considerably from the Eunichi flora in South Korea which has been considered by the present writer to be of the Miocene, indicating fairly

wormer climatic condition than it is in South Korea at the present time. In short, therefore, it is safe to conclude that the Meisen flora is fairly older than that of the Eunichi series and undoubtedly near in age to the Chōki flora, but not older than the latter.

c. Mankodō formation. A series of crossbedded sandstones, intercalating layers of conglomerate, shale, coal, etc. and marly nodules and accompanied by effusive sheets as well as intrusive bodies of olivine-basalt, covers an extensive area in the central hilly belt. They constitute the Mankodō formation. It contains numerous remains of marine molluscs preserved fairly well and attains about 1000 metres in thickness.

When the enormous thickness had these sediments reached, there took place in the present district a great tectonic movement which produced somewhat intricate system of faults as shown on the geological maps. The fault lines trend in some places diversely but in general approximately N.25°E. and their northwestern sides were thrown down. There are, however, a few, southeastern sides of which are considered to have been thrown down. The result of the movement, therefore, is the structure of horst, the central hilly belt corresponding, at least in part, to a basin, produced at this time.

So far as we are aware, physiognomy of North Korea, especially of North and South Kankyo-Dō, has been greatly controlled by a number of fault belonging to the system which produced the structure of horst in the present district. As one of the instances of analogous geological structure with that of the present district, due to the same system of fault, the writer can take that of the Kankō district⁽⁷⁾ in South Kankyo-Dō. On account of this, the writer has colligated tentatively the fault lines in question under the name of the Kankyo system, though it is highly probable that the system is contemporaneous with and belongs to the Sout' Korean Hansan system of Prof. Kotō,⁽⁸⁾ on which the writer has already stated⁽⁹⁾ that at any rate, it shows a greatest diastrophic movement which assailed the Circum Japan Sea region in the Cainozoic time and is considered to be highly important as a criterion in correlating the Cainozoic rocks in that part of the world. As for the significance of the Kankyo system, the writer states provisionally only that the block faulting at this time as recognized in North Korea seems to play a certain important role in the genetical relation of the Sea of Japan as well as the Japanese Islands lying on the opposite side of it.

Exact geological age in which the fault system was produced has not yet been known. Judging from the stratigraphical relations, however, it is no doubt considerably older than the Shichihōsan group, the youngest division of the Tertiary system in this district as described below.

Approximately in this stage of these movements the district became land and was subjected to degradation; and after it had been considerably eroded and had nearly lost in places its characteristic features due to the faults, a large amount of alkalic lavas commenced to be poured out successively, mainly from the vicinity of Shichihōsan in the coastal mountainous belt. They are the rocks of the Shichihōsan group.

Shichihōsan group. Besides various kinds of alkalic rocks covering an extensive area in the coastal mountainous and the central hilly belts, it includes a small amount of tuff, volcanic breccia, gravel, etc. which closely associate with the alkalic rocks. It is noteworthy that the group is lithologically very near to the complex of volcanic rocks constructing the main part of the Oki Islands⁽¹⁰⁾ in the Sea of Japan.

The group can be divisible into eight rock formations enumerated from the oldest as follows:

a. Zaitekusan alkalic basalt.

b. Naisandō formation.

c. Jōyōhō alkalic rhyolite.

d. Fukyō alkalic rhyolite.

e. Sōhō trachyte.

f. Shichihōsan alkalic granite-porphry.

g. Jigan formation.

h. Shichihōsan alkalic rhyolite.

a. Zaitekusan alkalic basalt, the oldest formation of this group, covers unconformably the rocks of Meisen group and consists of at least four effusive sheets of basalt, attaining in general about 40 metres in the entire thickness. The four sheets, enumerated from the lowest one, are as follows:

No. 1: Olivineless basalt with titanomagnetite, anorthoclase? and biotite.

No. 2: Olivine-basalt with anorthoclase?

No. 3: Olivine-basalt comparatively rich in anorthoclase.

No. 4: Olivineless hypersthene-basalt with anorthoclase.

b. Naisandō formation consists of a variegated tuff, whitish, yellowishgrey, palegrey, etc. in colour, pumiceous, in places lithic, and accompanied in one place by boulder deposits. It is in general about 20 metres or less in thickness.

c. Jōyōhō alkalic rhyolite either covers the preceding rocks as strong sheets or cuts as dykes the schistose granites and the rocks of Meisen group and is widely distributed in the southern part of the present district. It consists essentially of greyish, purplish or brownish lithoidal rhyolite with or without spherulitic or banded structure, accompanied in some places by its agglomerate and glassy modifications. It is not rarely slightly porphyritic, being imbedded by small amount of phenocrysts of feldspar, with or without schillerization, and quartz.

d. Fukyō alkalic rhyolite covers the preceding as strong sheets, occupying but small areas in several places. Petrographically it is represented by a palegreyish fine grained rock imbedded by sparing phenocrysts of feldspar, with or without schillerization, and quartz. Microscopically it consists of a groundmass made of a fine aggregation of alkalic feldspar, quartz, riebeckite, senigmatite, aegirite-augite, etc., imbedded by a small amount of phenocrysts of alkalic feldspar and quartz.

e. Sōhō trachyte is represented by a porphyritic rock, consisted of a grey or darkgreyish groundmass imbedded by phenocrysts of alkalic feldspar and aegirite-augite? It occurs as small dykes cutting the Jōyōhō alkalic rhyolite or as sheets covering the same and is very limited in distribution.

f. Shichihōsan alkalic granite-porphry constitutes, together with the Jigan formation and Shichihōsan alkalic rhyolite, the southern precipitous part of the Coastal mountainous belt in the present district. In part, it clearly consists of a number of effusive sheets resting upon the schistose granites but in part seemingly massive. Modes of occurrence together with its lithological textures observed at various parts of its tract seem to suggest that in the southern part of the tract there was the vent from which the lavas of this formation were poured out.

The main bulk of the mass of this formation belongs lithologically to a porphyritic rock consisted of palegreyish groundmass which, according to the microscopical study, is microfelsitic or glassy and contains minute crystals of feldspar, quartz, kafofrite, arfvedsonite?, riebeckite, etc., imbedded richly by phenocrysts of alkalic feldspar, with or without schillerization, quartz, kafofrite, arfvedsonite? barkevikite, aegirite-augite, etc. Rarely it is

accompanied by glassy modifications.

g. Jigan formation consists of a series of volcanic breccias intercalating thin sheets of alkalic rhyolite which is similar in its petrological nature to the Shichihōsan alkalic rhyolite, mentioned just below. It attains about 180 metres in thickness.

h. Shichihōsan alkalic rhyolite appears in the various places in the southern part of the district, covering various preceding rocks as strong sheets or cutting them as dykes. Petrologically they belong to a grey or palegrey porphyritic rock characterized by its beautiful phenocrysts of moonstone. According to the microscopical study it is distinctly porphyritic consisting of glassy, microfelsitic or microspherulitic groundmass imbedded by alkalic feldspar mostly with schillerization, quartz, aegirite-augite, barkevikite, etc.

Gengen group. In the vicinity of the southeastern corner of the present district there is another group of rocks which rest upon the deeply eroded surface of the schistose granite and whose relations to the preceding groups are not known. In this Atlas they are tentatively included in the Tertiary system and grouped under the name of the Gengen. It embraces a basalt, accompanied by its tuff and agglomerates and a bed of conglomerate; and is divided into two formations as follows:

a. Gengen basalt.

b. Kan-enchi conglomerate.

a. Gengen basalt includes effusive sheets and dykes of olivine-basalt, accompanied by tuffs and agglomerates.

b. Kan-enchi conglomerate consists of conglomerate, probably more than 150 metres in thickness, dipping gently to the southeast. The pebbles constituting the bed are of well water worn and generally over 5 centimetres across. They are made either of basalt derived no doubt from the Gengen basalt, on which they were deposited, or shisitae granite, but none of them are shown to be of the rocks of Shichihōsan group. It is probably older in age than the Shichihōsan.

QUATERNARY SYSTEM.

Pleistocene series. Though we have no palaeontological evidence showing its Pleistocene age, I take provisionally, on the basis of stratigraphical relations, that geological age for these rocks which are considerably younger than the rocks of Shichihōsan group but can not be considered as younger as the Recent.

The series in question embraces basalt, trachyte, gravel, sand, clay, peat, etc. and are divisible into six formations as follows:

a. Kinzan formation.

b. Gyōrōsen basalt.

c. Seisandō formation.

d. Kyōkudō basalt.

e. Shikodō trachyte.

f. Yūtoku basalt.

a. Kinzan formation. In the various places of the central hilly belt, are appeared gravel beds, constructing upper portion of hills and covering unconformably the Tertiary rocks above referred to. Analogous gravel beds are also seen under the Gyōrōsen basalt and the Shikodō trachyte. They are conveniently grouped and described under this formational name. It consists largely of gravel, intercalating in places layers of clay rarely with impressions of plant, and attains about 30 metres in the thickest bed constructing the upper part of Kinzan, a hill in the vicinity of Meisen.

b. Gyōrōsen basalt extends widely along the course of the Gyōrōsen, forming here and there dissected lava plateaus of about 100 to 300 metres high above the adjacent alluvial tracts,

on the ground of the Tertiary rocks and schistose granites, the total thickness of the lava being approximately 100 metres. Rarely it covers thin gravel bed included into the Kinzan formation. Lithologically it is less variegated than the other basalts in this district and belongs to olivine-basalt commonly with ophitic structure.

e. Seisandō formation covers the preceding at Seisandō, about 10 kilometres northeast of Meisen, and consists of gravel, sand, clay and peat. It is thin, only several metres in thickness.

d. Kyokudō basalt embraces numerous effusive sheets of basalt, accompanied in some places by a small amount of agglomerate and forms an extensive lava plateau dissected by the lower stream of the Gyōrōsen and its tributaries. The plateau is low in altitude in comparison with those consisted of the Gyōrōsen basalt, thus exhibiting a lower step of the latter. The total thickness of the lava attains over 100 metres in general. It covers in some places thin and impersistent beds of gravel. Lithologically it is classified into two, viz. hypersthene-basalt and olivine-basalt, the latter rich in glass base.

e. Shōkodō trachyte is distributed in several places on the coast of the district, where it underlays the rocks of Kinzan formation and embraces sheets and dykes of variegated leucocratic trachytes with or without phenocrysts of quartz. At Shōkodō it is accompanied by multiformous glassy and agglomeratic modifications. No relations of these rocks to the preceding Pleistocene rocks except the Kinzan formation is known.

f. Yūtoku basalt is seen in several places, covering as a whole but a small area. It consists essentially of effusive sheets of basalt covering the rocks of Kinzan formation, Shōkodō trachyte or Tertiary system. The youngest rock among those of the Pleistocene, therefore, is the basalt under consideration or the Kyokudō basalt already referred to. Lithologically it belongs to olivine-basalts with or without analcime.

Recent series. It includes gravel, sand, clay, peat, mud, talus, etc., and is classified into three formations as follows:

- a. Old fluvialite formation (or Terrace deposits).
- b. Young fluvialite formation, together with the recent beach deposits.
- c. Talus formation.

INTRUSIVE ROCKS OF UNKNOWN RELATION.

Besides the rocks, of which relations are more or less closely known stratigraphically, there are a number of intrusive rocks of which mutual relations have not been utterly known. These are divided into two groups, viz.

- a. Rocks intruding into the schistose granite.
- b. Rocks intruding into the Tertiary rocks.

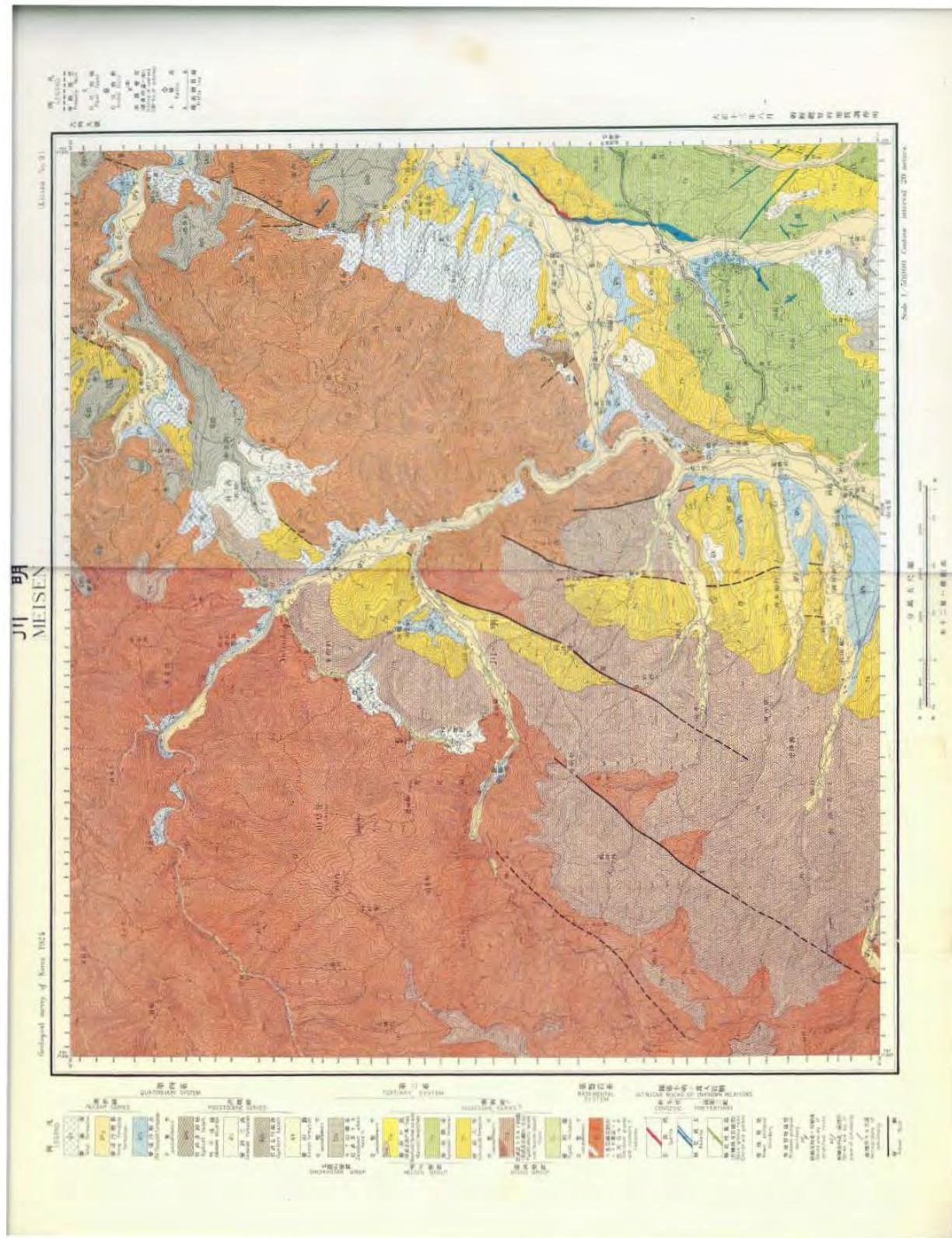
a. **Rocks intruding into the schistose granite.** This group is divisible into two subgroups, viz. 1, basic rocks including small dykes, dioritic or gabbroic in natures, mostly highly decomposed; 2, acidit rocks including small dykes of fine granite, granite-porphry, aplite and pegmatite. Most of them may rather appropriately be classed in the Basemental system.

b. **Rocks intruding into the Tertiary rocks.** The second group embraces the rocks intruding into the Tertiary rocks together with some dykes which intrude into the schistose granites but are considered from their lithological nature to be considerably younger in age, than the preceding one. These intrusive rocks includes basalts, rhyolites and syenite, mostly more or less alkalic in their lithological natures. Some of them may be highly interesting to petrologist.

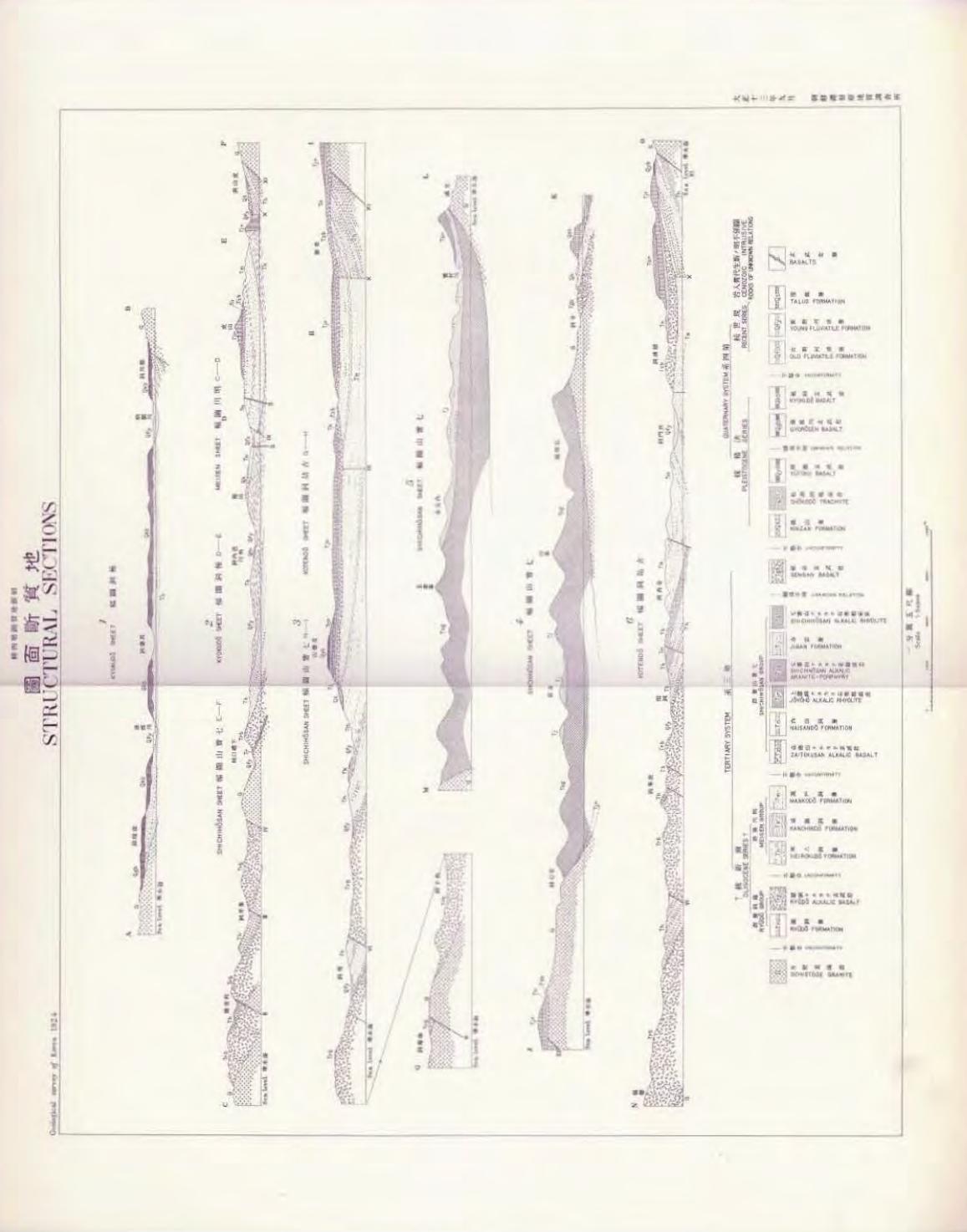
- (1) The field works which furnished all data for this Atlas were carried out during the months of May to August and October, 1922, and June to July, 1923.
- (2) Geological Atlas of Chōsen, No. 3.
- (3) S. Kawasaki: Mica in Chōsen with special reference to phlogopite in the Macromylonite series of Kankō-Dō. Bull. on the Mineral Survey of Chōsen, Vol. I, pt. 2, 1916.
- (4) I. Tateiwa: Geological Atlas of Chōsen, No. 2, 1924.
- (5) S. Tsuboi: On a Lencite Rock, Vulsinitic Viscosite, from Utsuryō Island in the Sea of Japan. Journ. Geol. Soc. Tokyō, Vol. XXVII, No. 327, 1920.
- (6) A. G. Nathorst: Zur Fossilien Flora Japan's. Palaeont. abhandl. herausgegeben v. W. Dames u. E. Kayser, Bd. IV, Heft 3, 1888.
- (7) Geological Atlas of Chōsen, now in preparation by the present writer.
- (8) B. Koib: An Orographical sketch of Korea. Journ. Sc. Coll. Tokyō, Vol. XIX, Art. 1, 1903.
- (9) Explanatory text to the Geological Atlas of Chōsen, No. 2 (Résumé) 1924,
- (10) S. Kōza: Petrological Notes on the Igneous Rocks of the Oki Islands. Sci. Rep. Tōhoku Imp. Univ. (Geological series) Vol. II, No. 1, 1913.

Postscript. Mr. J. Makiyama, Assistant Professor of Geology, Kyōto Imperial University, studied, at my request, the Molluscan faunas from the Meisen group, collected by the present writer in the Meisen district and by Mr. F. Yamazaki in the Kisshō district, and has recently showed me the following list of his determinations of a fauna, yielded from a lower part of the Hira-kodō formation, the lowest division of the Meisen group, at Nanseki, 7 kilometres northwest of Koten-dō, with a remark that the small fauna can not be the Neogene in age.

- Baillaria tateiwa Makiyama n. sp.
B. yamanarii Makiyama n. sp.
Potamides (Cerithidae) kapokensis Makiyama n. sp.
Acula submirabilis Makiyama n. sp.
Cyclina meisensis Makiyama n. sp.
Pecten nansekiensis Makiyama n. sp.
Yoldia sp.



Meisen Quadrangle Geologic Map, from Folio #4, 1925, Japan.
Area is just east of the Punggye-ri Nuclear Test Site (source Buttleman and Matzko, USGS)

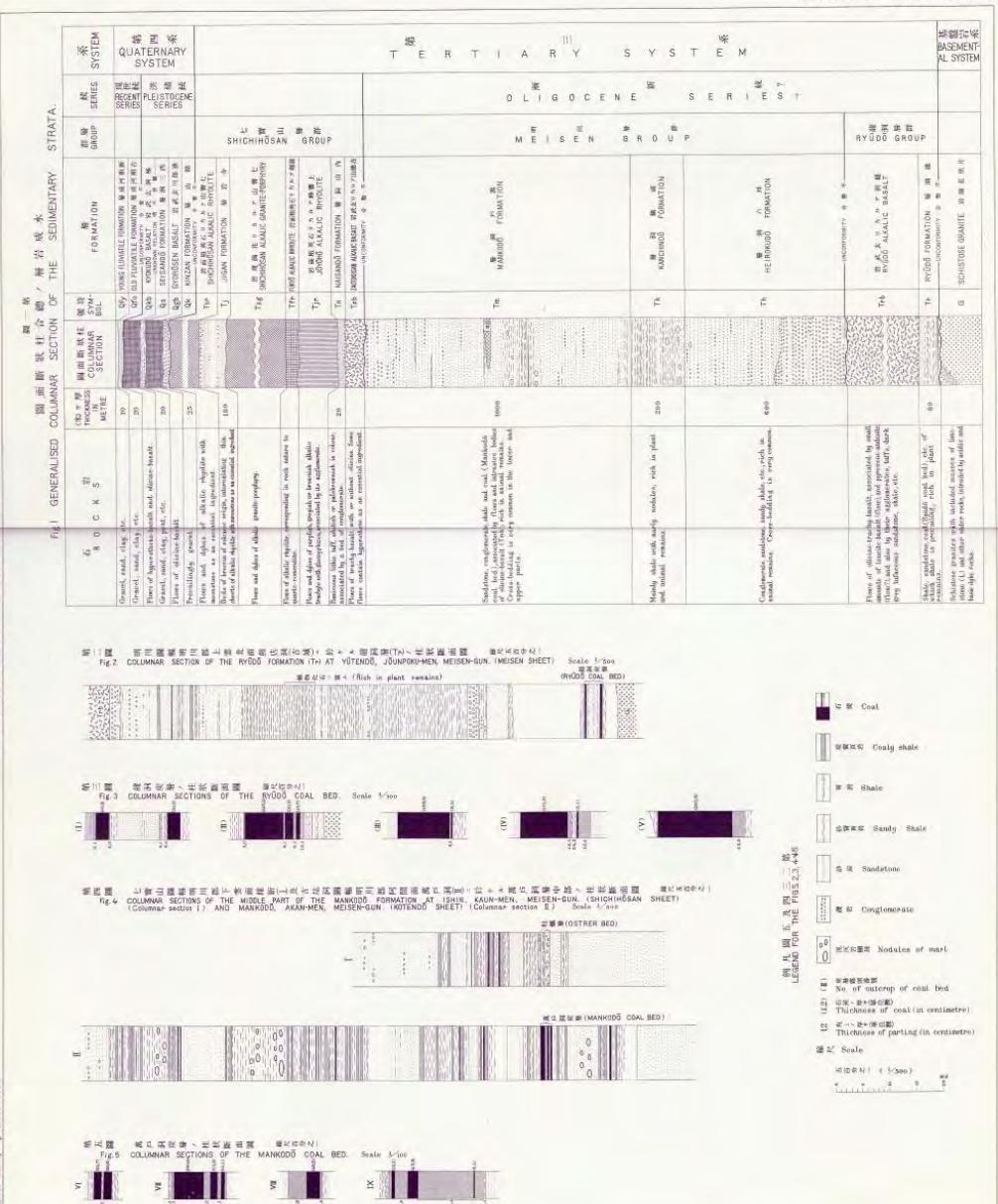


Cross-sections from Folio #4 just east of the Punggye-ri Nuclear Test Site

Source: Collection and Digitization of Data from Geological Atlas of Chosen Folio No. 4
Kyukudo, Meisen, Shichichosan and Kotendo Sheets by Iwao Tateiwa, Geological Survey
Governor General of Chosen Kokamondori Seoul 1925
(Source Buttleman and Matzko, USGS)

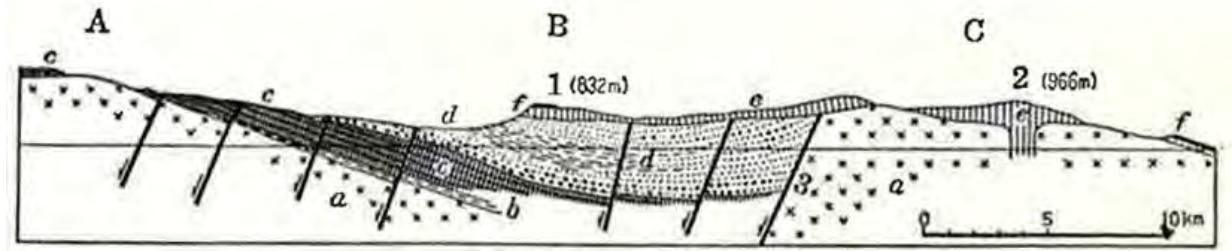
柱状圖
柱狀圖
COLUMNAR SECTIONS

Geological Survey of Korea 1924



Stratigraphic sections from Folio #4 just east of the Punggye-ri Nuclear Test Site

Source: Collection and Digitization of Data from Geological Atlas of Chosen Folio No. 4 Kyukudo, Meisen, Shichichosan and Kotendo Sheets by Iwao Tateiwa, Geological Survey Governor General of Chosen Kokamondori Seoul 1925
(Source Buttleman and Matzko, USGS)



A. Kaema Plateau	B. Kilchu-Myeongch'eon (Kilju-Meisen) Graben	C. Ch'ilbosan Horst
1. Chaeteok-san	2. Ch'ilbo-san	3. Kilchu
A. Basement Complex	b. Yongdong (Ryudo) Coal-bearing Formation	
c. Yongdong (Ryudo) Alkaline Basalt	d. Mueongch'eon Series	
e. Ch'ilbosan Volcanic Series	f. Pleistocene Basalt	

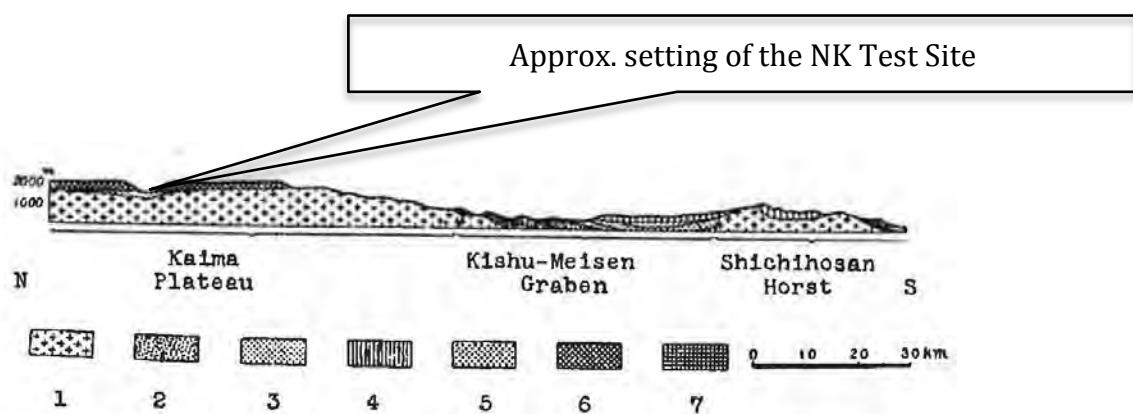


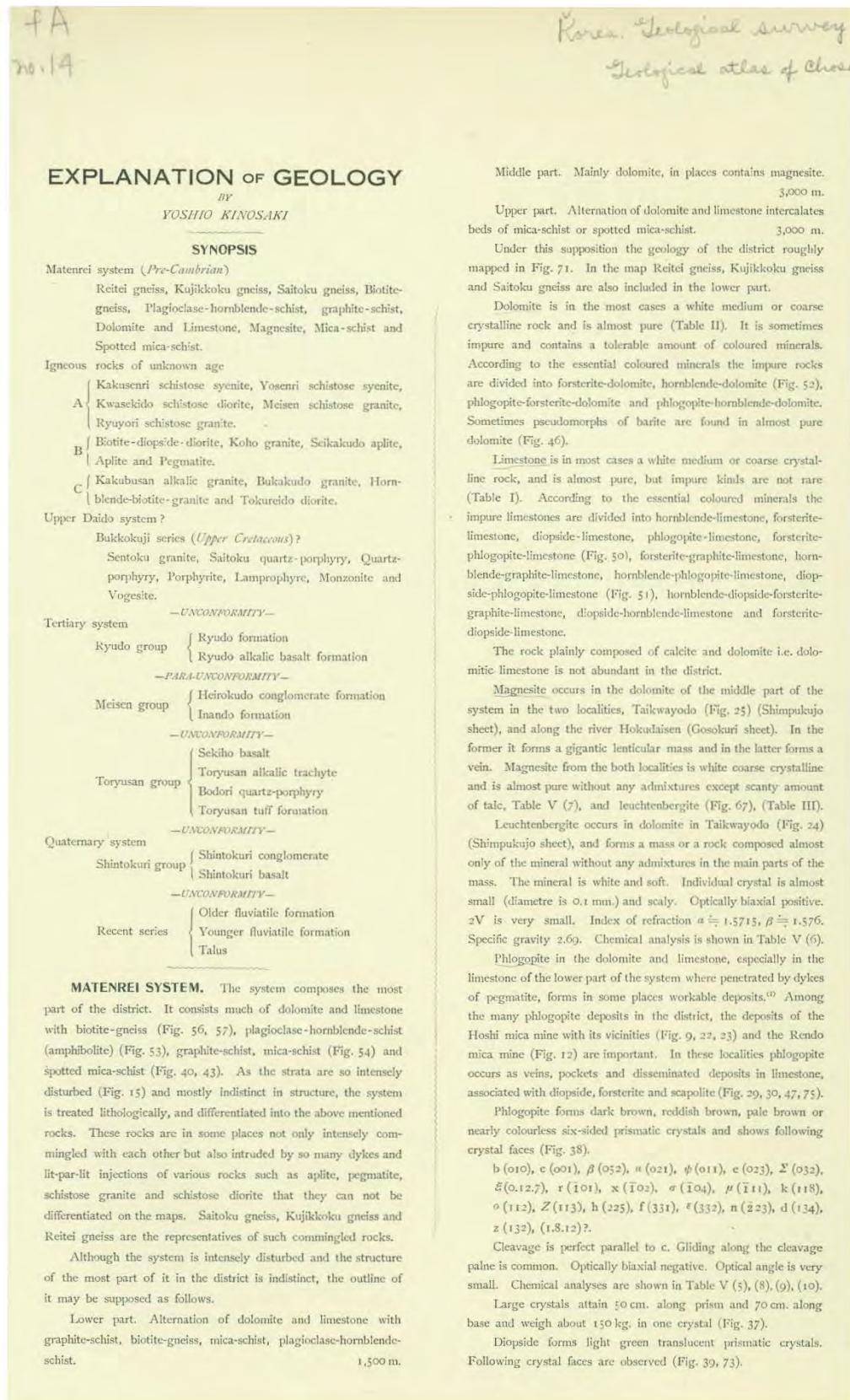
Fig. 2. Cross Section along the Southeastern Margin of the Kaima Plateau.

- | | |
|---------------------------------|--------------------------------|
| 1. Basal Complex. | 4. Shichihosan Group. |
| 2. Ryudo Group. | 5. Pleistocene Deposit. |
| 3. Meisen Group. | 6. Pleistocene Volcanic Rocks. |
| 7. Basalt on the Kaima Plateau. | |

Cross-sections through the Kilju-Myeongch'eon graben (Meisen is referred to on DPRK maps as Hau) **Upper:** (Adapted from Tateiwa, Folio#4) From the Kotendo and Schichichosan Quadrangles just southeast of the Punggye-ri Nuclear Test Site) Source: Tsutomu Ogura, *Geology and Mineral Resources of the Far East, Vol. 2, 1952*, University of Tokyo Press, 1969, p.16. **Lower:** From Kobayashi (1933).

Cross sections show the general geologic setting of the North Korean Test Site with capping sedimentary and volcanic rocks overlaying a basement complex (undifferentiated intruded and stressed Jurassic age schistose granites/diorites and/or gneiss).

Appendix C: Folio # 14 Geology Summary (e.g., Saitoku) and Key Graphics



No. 14, 1932.

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a (100), b (010), c (001), m (110), p (101), z (021), u (111), s (111), o (221), e (011).

Cleavage is distinct parallel to a, b and m. Clear parting parallel to c is characteristic. Hardness 6. Specific gravity 3.28. $2E 110^\circ$. Optically positive. Plane of optical axes parallel to b. $\hat{c}X \approx 15^\circ$ in acute β . $\beta \approx 1.6785$. Large crystals attain 50 cm. along prism and 20 cm. along base. Table V (3).

Forsterite forms light to dark green translucent crystals. Following crystal faces are observed (Fig. 41, 74).

b (010), c (001), m (110), s (120), r (130), e (111), f (121), k (021).

Cleavage is distinct parallel to b and c. Hardness 6.5. Specific gravity 3.051. $X \parallel b$, $Y \parallel c$, $Z \parallel a$, $\beta \approx 1.6615$. Large crystals attain 40 mm. along prism. Table V (4).

Nephelite is rarely found in phlogopite deposits. It forms with itself a rock having sporadic impregnation of phlogopite and plagioclase. The rock forms dykes about 50 cm. wide penetrating limestone. The mineral is grey translucent and is pierced by white veinlets of cancrinite (Fig. 48). Optically uniaxial negative. Index of refraction $\omega \approx 1.534$, $e \approx 1.5305$. Chemical analysis of the mineral is shown in Table V (1).

Graphite-schist is a grey schistose rock. It is mainly composed of graphite, quartz, orthoclase, chlorite, actinolite, phlogopite and diopside (Fig. 58), Table IX (1), (3). Where the rock pierced by pegmatite there are found relatively large scales of graphite. Large scales of that kind are mined in some places as graphite deposits (Fig. 10, 31, 34, 35), Table V (4).

Relatively large crystals of sillimanite, staurolite, actinolite, tremolite and cordierite (Fig. 40, 42, 43) and mineral deposits of gold, silver, copper, zinc, lead, iron and titanium (Fig. 13, 21, 28, 68, 69, 70) are found in the system.

The system⁽¹⁾⁽²⁾ belongs to the one of the three supposed Pre-Cambrian systems in Chosen, but as to its strict geological age nothing is known at present.

IGNEOUS ROCKS OF UNKNOWN AGE. Matenrei system is intruded by many kinds of igneous rocks which are supposed to be older than the Bukkokujian. The igneous rocks might have been intruded in several times between Pre-Cambrian to Bukkokujian, but nothing the geological age of each intrusion nor the strict intrusive relations among the igneous rocks themselves in most cases is known.

The igneous rocks contain granite, diorite, aplite, pegmatite, alkalic granite, and are according to the schistosity roughly grouped in three types, distinctly schistose (A) (Fig. 55), partly schistose (B) and not schistose (C). Each of the three types contains several rocks as shown in the synopsis.

Kakusenri syenite consists of schistose biotite-syenite, schistose diopside-biotite-syenite, schistose biotite-hornblende-syenite and schistose hornblende-syenite and contains many xenoliths of the Matenrei system.

Yosenri syenite consists of schistose biotite-hornblende-syenite and is almost free from small xenoliths. Chemical analysis of the rock is shown in Table IV (7).

Pegmatite belongs in most cases to the ordinary kind, and consists mainly of quartz, feldspar and mica, but one found near the Hoshi mica mine belongs to alkalic type. The alkalic pegmatite occurs as a dyke, about 30 m. wide, with the trend of N. 30° W. in dolomite. It consists mainly of aegyrite-augite and quartz, accompanying a little of orthoclase and titanite (Fig. 26).

Aegyrite-augite of the pegmatite is a black prismatic mineral and shows following crystal faces (Fig. 44, 45, 72).

a (100), m (110), b (010), e (011).

Parting nearly parallel to c is distinct. Specific gravity is 3.46. Strongly pleochroic, a deep green, B light green, r yellow; $a > B > r$. Optically biaxial negative. Plane of optic axes parallel to b. $\hat{c}X \approx 15^\circ$ in acute β . Large crystals attain 2 m. along prism. Chemical analysis of the mineral is shown in Table V (2).

Kakubusan alkalic granite is a light greenish medium grained rock. According to the component minerals the rock divided into aegyrite-granite (Fig. 60), aegyrite-riebeckite-granite, riebeckite-granite (Fig. 61) and aegyrite-biotite-granite. Chemical analysis of the aegyrite-granite is shown in Table IV (1), (Fig. 60, 61).

Seikakudo aplite consists of pegmatitic and aplitic rocks (Fig. 59) and contains many xenoliths of Matenrei system (Fig. 14).

Hot-springs are found in Onsendo and in its vicinity (Koho sheet). In the former the hot-springs gush out along the fissures in Koho granite (Fig. 33, 36), Table X.

UPPER DAIDO SYSTEM? In the district, Upper Daido system is represented by several igneous rocks of supposed Bulkokujin⁽²⁾ series, (formerly called Fukkokujin⁽²⁾ series), and are represented by surface flows, dykes, and partly porphyritic granite (Fig. 16, 17, 62). As these rocks are closely resembling certain igneous rocks of the Bulkokujin series in Chosen, it is supposed that the rocks may be included in the series, but as for the strict geological age of the rocks nothing is known in the district.

TERTIARY SYSTEM. Ryudo and Meisen groups consist of alkalic basalt flows and terrigenous deposits with some coal seams (Fig. 11, 32). Ryudo alkalic basalt formation consists mainly of an accumulation of many flows of alkalic basalt intercalating tuff and sandstone (Fig. 27). The alkalic basalt is a black to grey aphanitic rock showing a tolerable amount of orthoclase under the microscope in thin section. Table IV (5). The groups contain some animal and plant remains.

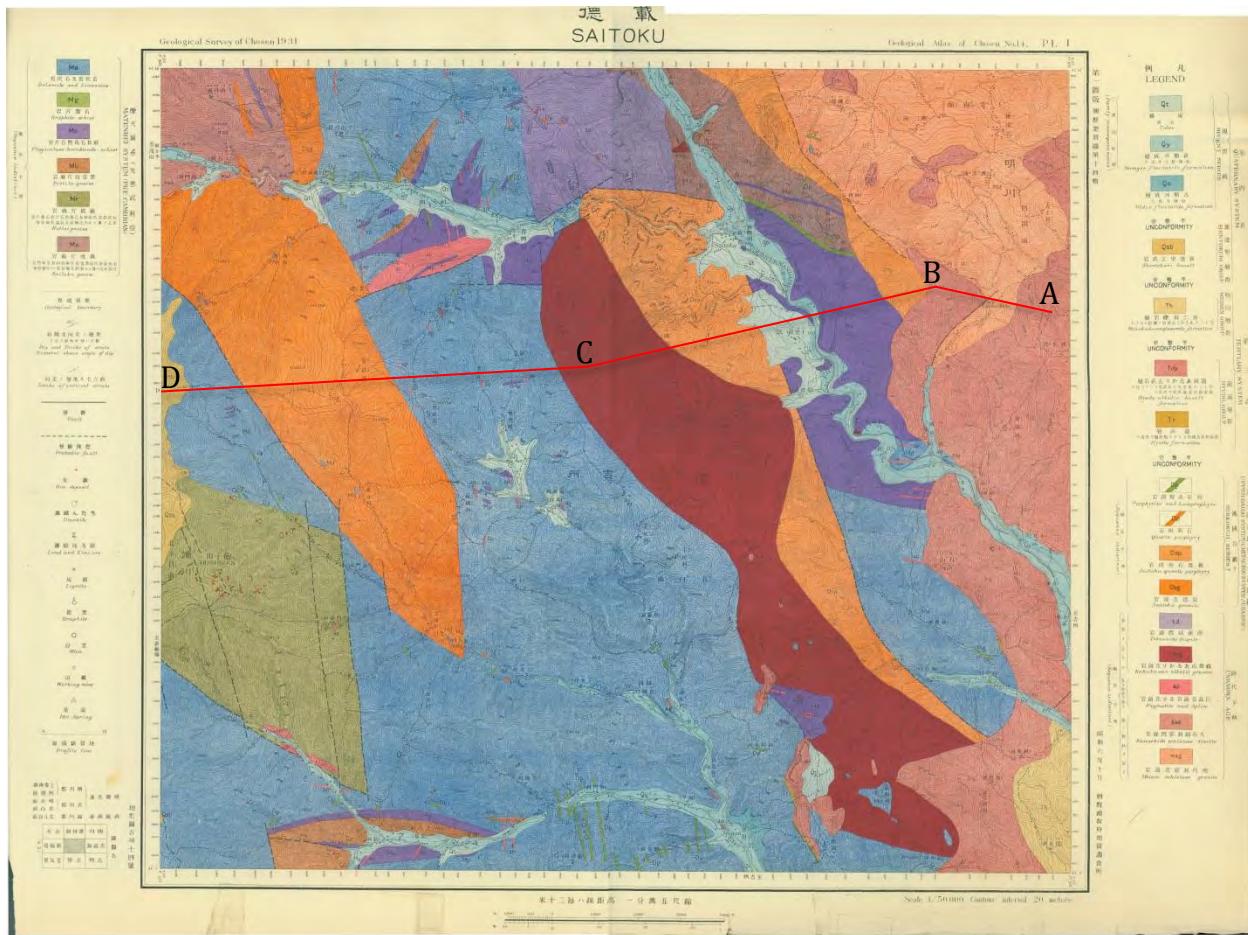
The plant remains of the groups are considered by Tateiwa⁽⁴⁾ as of Oligocene-Eocene, and Makiyama⁽⁵⁾ regards the animal remains of the lower⁽²⁾ part of Meisen group (Heirokudo conglomerate formation and Inando formation in this district correspond to the lower part of Meisen group) as of Upper Eocene.

Toryusan group consists mainly of volcanic flows and tufts (Fig. 18). Sekiho basalt is an accumulation of many thin flows of olivine-basalt (Fig. 66). Toryusan alkalic trachyte consists of surface flows. In the district the eruptive centre of the flows is supposed to be Mt. Toryusan which occupies the northwestern corner of the district and lies at the southern end of the Hakuto⁽⁶⁾ volcanic range. The alkalic trachyte is a grey porphyritic rock with phenocrysts of anorthoclase. The ground mass of the rock consists of alkalic feldspar, aegyrite, aegyrite-augite, barkevilkite, riebeckite, aenigmatite and glass (Fig. 63, 64). Table IV (2). Toryusan tuff formation consists mainly of tuff of alkalic trachyte, Table IV (3), with fragments of alkalic trachyte, obsidian and beds or fragments of pumice (Fig. 65). The strict geological age of the group is not distinct, but it is considered from the stratigraphical and petrographical characters to be the same age as of the Shichihosan⁽⁷⁾ group of supposed younger Tertiary.

QUATERNARY SYSTEM. Shintokuri basalt of Shintokuri group is an accumulation of thick flows of olivine-basalt. The area of the basalt in the district belongs to the southern margin of a great mesa of basalt around Mt. Hakutosan (Fig. 19, 20), Table IV (6).

LITERATURES

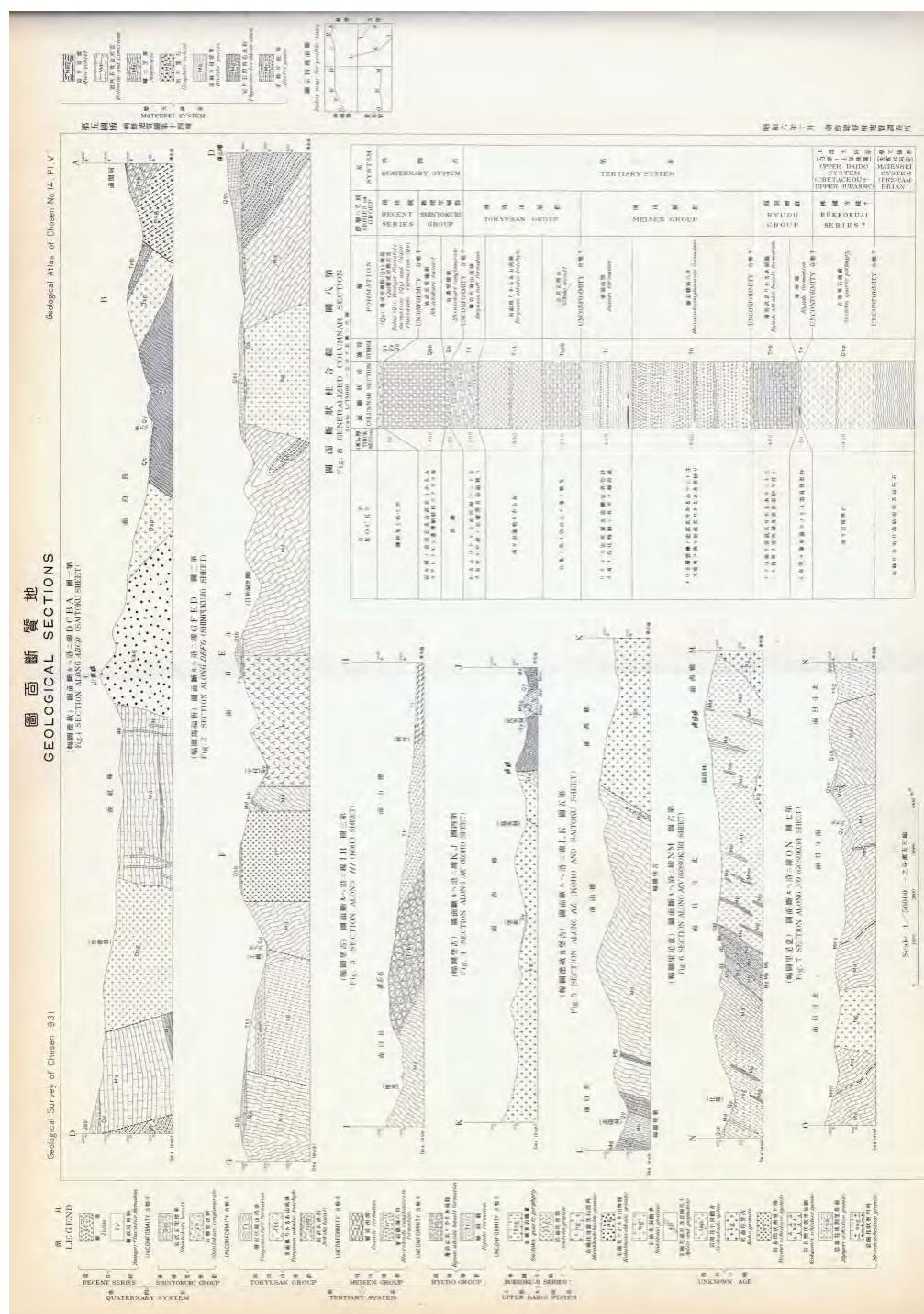
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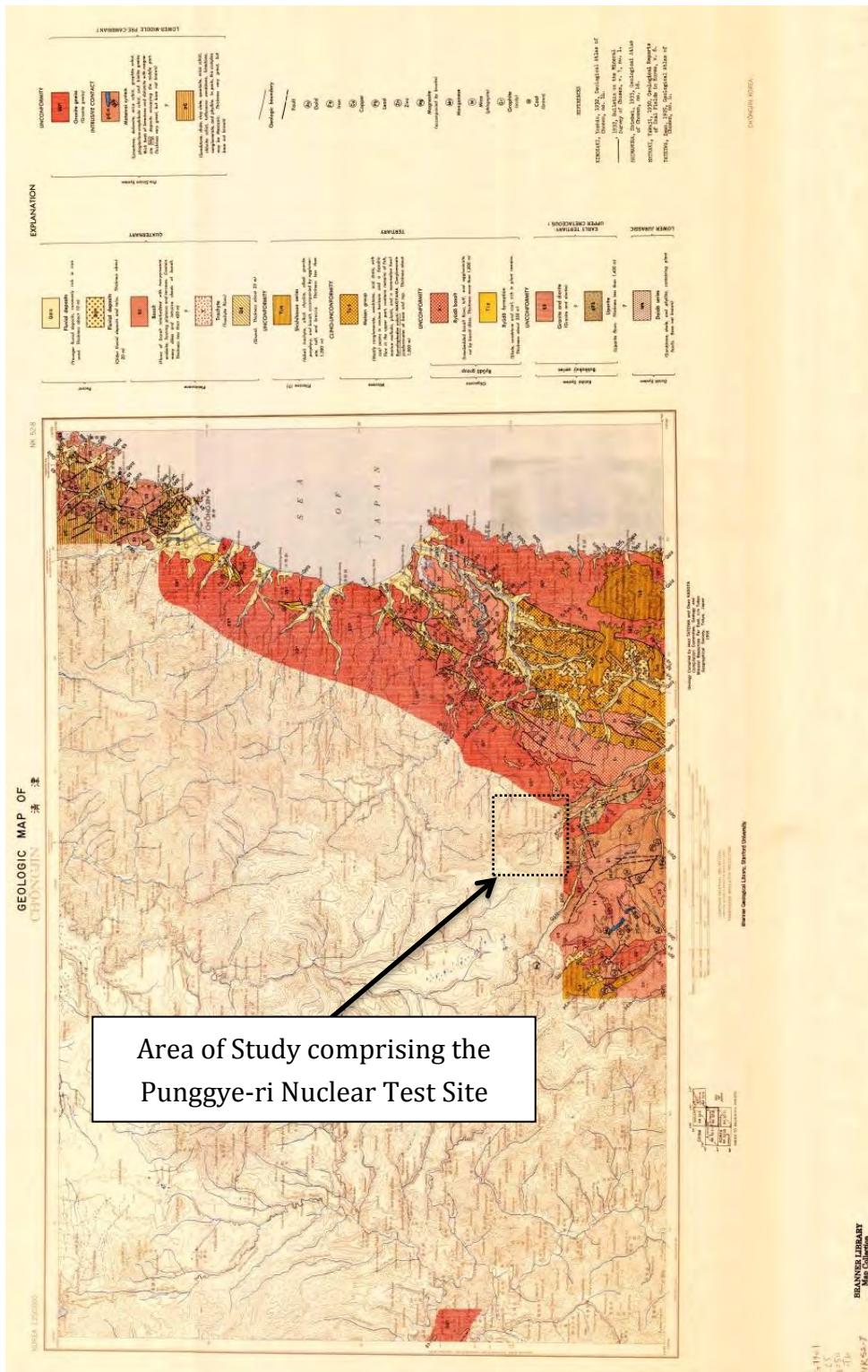
Saitoku (Punggye-ri) Quadrangle Geologic Map, from Folio #14, 1932, Japan.
Area is just south of the Punggye-ri Nuclear Test Site



Geological Cross-section from Saitoku Quadrangle, about 20 kilometers south of the Punggye-Ri Nuclear Test Site, from Folio #14, 1932, Japan
(Source Buttleman and Matzko, USGS)



Cross-sections with Legend and Columnar section from Folio #14 just south of the Punggye-ri Nuclear Test Site Source: Collection and Digitization of Data from Geological Atlas of Chosen Folio No. 14 Saitoku, Shimpukujo, Koho, and Gosukori, Sheets by Yoshio Kinoshita, Governor General of Chosen Geological Survey Kokamondori Seoul July 1932 (Source Buttleman and Matzko, USGS)



Geologic Map of Chongjin, 1955, Japan

The geology of the area of study comprising the Punggye-ri nuclear test site was not mapped. (Scan courtesy of Jane Ingalls at Stanford University)

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² As carbonate material, dolomite/limestone, when vaporized in a nuclear event, forms incondensable carbon dioxide gas, which, if created in large enough quantities, can act as a driving force to transport radioactivity through the overlying rock to the surface. Dolomite/limestone is therefore considered unsuitable as a host rock for containment of nuclear explosions. Source: U.S. Congress, Office of Technology Assessment,

The Containment of Underground Nuclear Explosions, OTA-ISC-414 (Washington, DC: US Government Printing Office, October 1989)

³ “Meisen Schistose Granite” is the name given by Japanese geologists who mapped the area in the 1920s and 1930s. It refers to a granitic basement rock of unknown age, but likely Jurassic, that was sufficiently altered to exhibit “a more or less distinct banded flow structure” (typical of what would normally be referred to as “gneiss”). Moreover, the reporting states, “Such granites are discordantly covered by Lower Cambrian beds (e.g., dolomite/limestone) of the Chosen system in various places in Korea and have been well known among Korean geologists under the name “gray granite-gneiss,” the typical granite being the Kanko gneiss which (Tateiwa) discovered in the Hamgyong Province”. Iwao Tateiwa, “Synopsis of the Geological Systems of Korea,” *Geology and Mineral Resources of the Far East, Vol 1*, 1952, republished by the University of Tokyo, 1967.p. 11. **NOTE: In the Korean geologic literature of the post-Japanese period, the Japanese rock and formation names have been discarded and replaced with Korean terminology, complicating the correlation of geologic units between the two periods.**

⁴ “Diorite is an intrusive rock intermediate in composition between gabbro and granite. It is produced in volcanic arcs, and in mountain building where it can occur in large volumes as batholiths in the roots of

mountains (e.g. Scotland, Norway). Because it is commonly speckled black and white, it is often referred to as "salt and pepper" rock.” http://flexiblelearning.auckland.ac.nz/rocks_minerals/rocks/diorite.html

⁵ It should be noted that following the February 11, 2013 test; radionuclides were detected at two CTBTO monitoring stations. “*Two radioactive isotopes of the noble gas xenon were identified, xenon-131m and xenon-133, which provide reliable information on the nuclear nature of the source. The ratio of the detected xenon isotopes is consistent with a nuclear fission event occurring more than 50 days before the detection (nuclear fission can occur in both nuclear explosions and nuclear energy production). This coincides very well with announced nuclear test by the DPRK that occurred on 12 February 2013, 55 days before the measurement.*” “*After an underground nuclear explosion, radioactive noble gases can seep through layers of rock and sediment until they escape into the air. Alternatively, the radioactivity may also be released by man-made activities at the test site.*” <http://www.ctbto.org/press-centre/press-releases/2013/ctbto-detects-radioactivity-consistent-with-12-february-announced-north-korean-nuclear-test/>

Given the lack of any venting in the likely same host rock following the 2009 test, and the relatively long delay in release of material following the 2013 test, the question arises as to what might have caused such a release. A review of high resolution imagery of the test site following the 2013 test shows significant activity occurred at the tunnel portal (vehicle tracking and tunneling activity)... suggesting that rather than being an issue of host rock competency, human activity (e.g., re-entry) may have triggered the release. See: New Tunneling Activity at the North Korean Nuclear Test Site, *38 North*, 25 June 2013.

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